



Is Europe prepared to live without emissions? A dynamic analysis of the energy transition in economic sectors

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Abstract

Europe has experienced the adverse effects of climate change due to the human footprint on a scale never seen before. The region's future appears challenging as it persistently adheres to conventional practices. To address this, social movements in Europe must advocate for policymakers to earnestly undertake the widely advocated energy transition within the existing socioeconomic model. A crucial aspect for governments is to comprehend the status along the trajectory of this transition. In this study, we investigate the intricate relationship between emissions, economy, and energy spanning the years 1990 to 2019 across 32 European countries. Our analysis differentiates among major polluting sectors, utilizing a dynamic model that accounts for potential structural breaks. Our findings confirm the presence of ruptures in the stability of the parameters, revealing three distinct periods marked by historical shocks. While the majority of European countries exhibit a decoupling between emissions and economic growth, a contrasting trend is observed between emissions and energy consumption. Notably, the energy supply and residential sectors emerge as the most problematic due to their high carbon intensity. However, the decoupling process remains distant in terms of energy, underscoring the imperative shift toward renewable energy sources over conventional fossil-based fuels. This study emphasizes the urgency of adopting sustainable practices to mitigate climate change and encourages a reevaluation of current energy paradigms.

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1 Introduction

The consequences of anthropogenic climate change have already manifested globally. Currently, the excessive use of energy, primarily derived from fossil fuels, forming the foundation of our economic consumption and production patterns, has resulted in annual record-breaking greenhouse gas (GHG) emissions on a worldwide scale. No region is immune to the threats posed by global warming associated with climate change. Europe serves as a glaring example of this situation. The World Meteorological Organization (WMO) of the United Nations (UN), in its recent report on Europe (WMO 2021), portrays this continent as a vivid representation of a warming world. European temperatures have surged at more than twice the global average over the past 30 years, marking the highest increase among all continents. Specifically, between 1991 and 2021, temperatures in Europe have risen significantly at an average rate of about +0.5 °C per decade. As the warming trend persists, the societal, economic, and ecological impacts of exceptional heat, wildfires, floods, and other climate-related events will continue to escalate.

A cursory examination of events reveals that sustained growth, accompanied by a reduction in natural resource consumption and environmental degradation, has yet to materialize. The renewed efforts of politicians and decision makers to decouple the economy, energy, and the environment fall short. Evidence suggests that civic activism, particularly in advanced countries, is to some extent linked with a structural shift in the pattern of environmental degradation (Adedoyin et al. 2020). Social pressure can compel policymakers to enact policies that advocate for reduced resource exploitation, increased use of clean energies, and a shift toward less energy-intensive activities. A pivotal aspect of these policies is the well-documented energy transition of the socioeconomic model (Antonakakis et al. 2017; Waheed et al. 2019). It is imperative to decrease the ecological footprint in the coming decades without compromising societal well-being, achieved through the decarbonization of all economic sectors by conserving resources, altering the energy mix in favor of renewables, and supporting less energy-intensive activities. Unfortunately, this transformation is not occurring to the extent and at the pace required to combat climate change (Bithas and Kalimeris 2013).

In recent years, scholarly debates on decoupling have intensified in response to this structural challenge and the understanding that the timelier implementation of appropriate measures will mitigate consequences for all. The literature from various empirical studies does not suggest absolute decoupling but indicates that relative decoupling is occurring sporadically in developed countries (Saidi and Hammami 2015; Wu et al. 2018; Chen et al. 2018; Shuai et al. 2019; Haberl et al. 2020; Vadén et al. 2020).

Emissions have not remained stagnant, mirroring economic growth, and energy consumption. A substantial body of work has sought to ascertain the intensity and direction of the relationship between the economy, emissions, and energy consumption (Lanne and Liski 2004; Lee et al. 2008; Lee and Lee 2009;

Lee and Chang 2009; Christidou et al. 2013; Ajmi et al. 2013; Presno et al. 2018; Cai et al. 2018; Zerbo and Darné 2019; Awaworyi Churchill et al. 2020; Wen et al. 2021). Similarly, the literature has reached a consensus on considering the static or dynamic analysis of this relationship over time as a crucial issue. Given the high degree of interrelation of emissions, the economy, and energy worldwide, it seems appropriate to examine the evolution of these socioeconomic parameters in light of possible structural changes. The assumption of parameter stability might not hold, given that certain abrupt global or country-specific events (e.g., economic downturns, financial crises, collapse of governments, natural disasters, and social protests) can alter it. Furthermore, it seems necessary to estimate the link between emissions, the economy, and energy while admitting the presence of multiple breaks.

This paper aims to contribute to this body of knowledge by studying the relationship between emissions, economic growth, and energy consumption across a wide range of European countries and economic sectors for the period 1990–2019. The analysis includes an assessment of the impact of historical events on the trends in the model's parameters, utilizing the methodology proposed by Bai and Perron (1998, 2003a, b) that is a robust option, as it endogenously determines both the number and the period in which structural breaks appear. This approach will facilitate an understanding of the evolution of estimated elasticities, providing useful information to assess the degree of coupling or decoupling among these variables in each country and economic sector.

Furthermore, this study aims to identify the real momentum of Europe on the path of energy transition in all economic sectors. This diagnosis is crucial for researchers to focus their efforts on the most lagging sectors and for policymakers to promote actions in favor of socioeconomic sustainability. Europe is an interesting case study due to three significant issues. Firstly, many countries are at the forefront of developing and implementing strategies and plans to preserve the environment. Additionally, Europe is one of the most advanced regions in transboundary cooperation for climate change adaptation. Secondly, despite being well-prepared societies, European countries are not immune to the impacts of extreme weather events caused by global warming. Instances include desertification in Portugal and Spain (the Iberian Peninsula), Alpine glaciers melting in France and Switzerland, droughts in southern Turkey and Greece, floods in the countryside in Germany and the UK, and rising sea levels in Belgium and the Netherlands. Thirdly, the spatial analysis of the relationship between GDP, energy consumption, and emissions in Europe highlights the nuanced interplay between economic development and environmental outcomes. Understanding these spatial variations is crucial for designing targeted policies that promote sustainable growth while mitigating environmental degradation.

The remainder of the paper is organized as follows. Section 2 provides a literature review of the linkages between environmental, economic, and energy variables, focusing on empirical work presented for Europe. Section 3 describes the data and analysis framework. Section 4 presents the empirical results of the unit root inference and stability among emissions, economic growth, and energy consumption in four economic sectors (energy supply, industry, domestic transport, and residential sectors) under the scope offered by the presence of structural breaks. Finally, Sect. 5 draws the most important conclusions and discusses key policy recommendations.

2 Literature review

The relationship of environmental impacts, economic growth and energy consumption has become a focal point for policymakers aiming to foster sustainable development aligned with ecological and resource objectives. This nexus has been a subject of rigorous academic scrutiny globally, with a growing empirical literature consolidating into three distinct lines of research (Tiba and Omri 2017). However, a lack of uniform findings across these lines persists, attributed to variations in time periods, focus on specific or multi-country samples, diverse econometric approaches, the application of individual or aggregate variables, and the potential for omitted variable bias.

The first line of research primarily delves into the bivariate link between economic growth and environmental quality, often measured through carbon dioxide emissions, utilizing the Environmental Kuznets Curve (EKC) hypothesis. While some studies, such as Vehmas et al. (2007), Saikku et al. (2008), Bhattacharyya and Matsumura (2010), Naqvi and Zwickl (2017), Madaleno and Moutinho (2018), observe a conjoint rise in emissions with economic development followed by a decline, others, including Kaivo-oja and Luukkanen (2004), Herrerias (2012), Padilla and Duro (2013), Juknys et al. (2014), Fernández González et al. (2014a), and Ulucak and Apergis (2018), reveal varying degrees of sustainability among European countries. The income level and, to a lesser extent, energy consumption factors are identified as crucial determinants, with ongoing convergence driven by these factors.

The second strand explores the causality between the economic growth-energy consumption link, presenting inconclusive findings for Europe. Studies like Chontanawat et al. 2008, Menegaki 2011, Belke et al. 2011, Bozoklu and Yilanci 2013, and Śmiech and Papież 2014, underscore the energy's importance but lack consensus on the nature of the relationship—whether unidirectional or bidirectional.

Building upon these connections, the third line investigates three-way linkages among environment, growth, and energy, focusing on the decoupling process. Research indicates that achieving sustainable economic growth while averting environmental degradation and energy resource depletion is a complex task, with varying degrees of success across European countries (Acaravci and Ozturk 2010; Kasman and Duman 2015; Cruz and Dias 2016; Moreau and Vuille 2018; Sanyé-Mengual et al. 2019). The literature emphasizes the necessity of an energy transition in socioeconomic structures to decouple the economy and energy from emissions, advocating for a shift toward consumption-focused policies (Liobikiene and Dagiliute 2016).

Recent studies by Morales-Lage et al. (2019) and Tagliapietra et al. (2019) underscore the importance of decarbonization policies across all economic sectors for advancing the European energy transition. Priority sectors include power generation, manufacturing, transport, and building, identified as significant contributors to emissions due to excessive energy consumption, predominantly from fossil sources. Sector-specific analyses, such as Liaskas et al. (2000),

Diakoulaki and Mandaraka (2007), Fernández González et al. (2014b), Karmellos et al. (2016), Kopidou and Diakoulaki (2017), Rodrigues et al. (2020), Karmellos et al. (2021), and Cialani and Mortazavi (2021), reveal substantial differences in carbon footprint evolution among sectors across countries and over time.

Regional disparities in CO₂ emissions and energy consumption in Europe are influenced by a complex interplay of factors such as socioeconomic conditions, demographic characteristics, policy interventions, and global economic processes. Understanding these spatial variations is crucial for designing targeted policies that address environmental challenges while promoting sustainable development and regional equality across Europe. Several studies offer valuable insights into these aspects, shedding light on the spatial disparities and the elasticity estimate of emissions, GDP and energy consumption across different European regions.

Studies by Bouzarovski and Tirado Herrero (2017), Flores-Chamba et al. (2019), and Abart-Heriszt et al. (2019) shed light on these issues, highlighting disparities in energy poverty, CO₂ emissions, and energy consumption across European regions. These studies stress the importance of targeted regional policies to address economic convergence and equality within and across European regions. Additionally, they emphasize the significance of factors such as renewable energy, employment in industry, and integrated spatial and energy planning in understanding spatial disparities and reducing greenhouse gas emissions. Furthermore, the study by Kilinc-Ata and Likhachev (2022) on the validation of the Environmental Kuznets Curve hypothesis in the Russian Federation provides insights into the impact of economic growth, financial development, and trade openness on emissions. It offers valuable perspectives on spatial disparities in emissions and the effectiveness of policies. Overall, all these studies highlight the importance of considering spatial disparities in economic policies, energy sources, and consumption patterns when analyzing the decoupling of CO₂ emissions from economic activities and GDP in Europe.

To understand the causes of disparities in emissions and economic growth decoupling in Europe, it is essential to consider the multifaceted nature of these disparities (Schandl et al. 2016). Their study discusses the aim of achieving economic growth while slowing the rate of natural resource use and emissions, emphasizing the concept of relative and absolute decoupling. This provides insight into the challenges of balancing economic growth with environmental sustainability. Furthermore, Shuai et al. (2019) present a three-step strategy for decoupling economic growth from carbon emissions, offering empirical evidence from 133 countries. This empirical evidence shed light on the factors influencing the disparities in emissions and economic growth decoupling, providing a comprehensive understanding of the complexities involved.

This study aims to contribute to this literature by examining the nexus between emissions, economic growth, and energy consumption in Europe. Given the centrality of decoupling in European environmental and industrial policies, our analysis becomes crucial. The literature suggests that relying solely on decoupling as a sustainability strategy may be inadequate, necessitating a shift from growth-as-usual approaches. The dynamic analysis of the emissions, economy, and energy relationship, incorporating nonlinear specifications and accounting for structural

breaks, offers a nuanced understanding of the decoupling hypothesis. Our study departs from previous static analyses, allowing for parameter changes over time, as advocated by González-Álvarez and Montañés (2023). By scrutinizing stationarity properties, we aim to identify cyclical fluctuations or changes in trends, distinguishing between relative and absolute decoupling.

Therefore, it is necessary to check the stationarity properties of the parameters to verify if there is a cyclical fluctuation or any change in the trend. A distinction must be made with previous literature, such as Gil-Alana and Trani (2019), Fallahi (2020), Caglar et al. (2021), and Ketenci (2021). A temporary stage in the growth rate of emissions lower than the respective rates of economic and energetic indicators (relative decoupling) means an increase in resource use and a decline in ecosystems. A change in the trend of the rate of emissions indicates an opposite direction with respect to economic and energy consumption growth (absolute decoupling), where environmental pressures decrease without a corresponding decrease in the economic sectors.

In conclusion, the existing literature underscores the intricate and evolving relationships among environmental impacts, economic growth, and energy consumption. Our study contributes to this discourse by adopting a dynamic analysis approach, offering valuable insights into the nature of decoupling processes and their implications for Europe's sustainability journey. In addition, we explore the spatial disparities in Europe regarding the decoupling of CO₂ emissions from economic activities and GDP that may be influenced by a multitude of factors, including economic policies, energy sources, and consumption patterns. Understanding these disparities is crucial for developing targeted strategies to minimize environmental impact and promote sustainable economic practices across different regions in Europe.

3 Materials and methods

3.1 Data source and description

This paper aims to investigate the interplay and trends in emissions, economic growth, and energy consumption across European countries. The study encompasses various economic sectors, including energy supply, industry, domestic and international transport, residential, livestock, agriculture, and waste. However, the primary focus is on four critical sectors: energy supply, industry, domestic transport, and the residential sector, collectively accounting for over three-quarters of total emissions across all countries in 1990 and 2019.¹ The analysis explores the nexus between CO₂ emissions from these sectors, each country's GDP, and energy consumption from 1990 to 2019.

Greenhouse gas emissions, measured in thousand metric tonnes of CO₂ equivalents, are reported for each country and the aforementioned economic sectors: energy supply, industry, domestic transport, and residential. These emissions were obtained from the European Environmental Agency (EEA) at both the

¹ The results of the rest of the economic sectors (international transport, livestock, agriculture, and waste) are not provided here, but they can be obtained from the authors upon request.

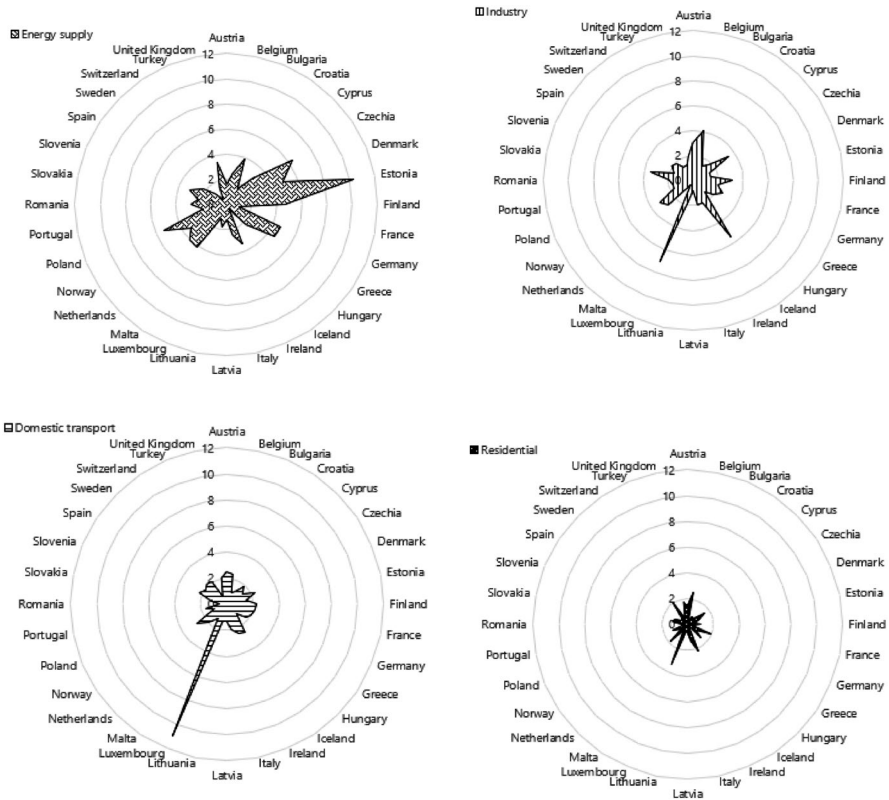


Fig. 1 Per capita CO₂ emissions by economic sectors (average 1990–2019)

country and economic sector levels, following the control methodology established by the United Nations Framework Convention on Climate Change (UNFCCC) for all signatory nations of the Kyoto Protocol 1997 and the Paris Agreement 2015. It is important to note that all European countries are included under these international agreements for emissions reduction.

Economic growth is expressed in terms of real Gross Domestic Product (GDP) in Purchasing Power Standards (PPS). Finally, primary energy consumption (EC) before any further transformation is measured in thousand tonnes of oil equivalent. These last two variables are sourced from the Eurostat database for each country. Summary statistics for each variable across countries (CO₂, GDP, and EC) are provided in Table 9 in Appendix A. The final sample is composed of 32 European countries for which data is available for all relevant variables during the period under analysis.

Each country exhibits distinct behavior, as depicted in Fig. 1. Certain countries exhibit significantly higher CO₂ emissions, with variations across sectors. For instance, energy supply is a major emitter for several countries, while others show higher emissions in industry, domestic transport, or residential sectors. The

energy supply sector emerges as the most environmentally harmful for Bulgaria, Czechia, Estonia, Germany, Hungary, Italy, Norway, Poland, Romania, Slovenia, and the UK. In contrast, for Austria and Slovakia, it is the industry sector, and for Luxembourg and Latvia, the primary concern is domestic transport.

This heterogeneous behavior persists when observing the average growth rate in CO₂, GDP, and EC (refer to Table 10 in Appendix A for detailed information). The sample is divided into two periods, 1990–2005 and 2005–2019), highlighting sector-specific emission reductions and increases. The analysis reveals a decrease in CO₂ emissions for the energy supply, industry, and residential sectors by – 1.9%, – 1.7%, and – 1.2%, respectively, in Europe. Notably, the decline in emissions has been more pronounced from 2005 onwards. Conversely, the domestic transport sector has experienced a 0.4% increase in emissions, although there is a noticeable shift in the strong positive trend toward a slight decrease after 2005.

Country-specific trends diverge, with some nations consistently reducing emissions, while others experience fluctuations. The paper underscores the heterogeneous nature of emissions reduction efforts, particularly in the energy supply and industry sectors. In the energy supply sector, certain countries exhibited a consistent decrease in emissions over the entire period, including the UK (– 4.0%), Lithuania (– 3.7%), Slovakia (– 3.5%), Romania (– 3.3%), Denmark (– 2.8%), Latvia (– 2.7%), Malta (– 2.7%), Estonia (– 2.4%), France (– 2.2%), and Germany (– 2.1%). Conversely, Luxembourg (11.9%), Turkey (3.3%), Iceland (2.5%), Norway (1.0%), Cyprus (0.8%), Finland, and Portugal (0.5%) were the sole countries that witnessed an increase in emission rates. Post-2005, while most countries experienced a decline in emissions from the energy supply sector, some showed an increase compared to the preceding period, as observed in Bulgaria, Estonia, Latvia, Lithuania, Poland, and Turkey.

In the industry sector, most countries demonstrated a noteworthy decrease throughout the years. Conversely, a few countries, such as Malta (5.0%), Turkey (1.0%), Iceland (0.9%), Lithuania (0.3%), Austria, Cyprus, and Portugal (0.1%), exhibited an increase. Similarly, almost every country increased the abatement rate in the period 2005–2019, with the exceptions being Bulgaria, Czechia, Estonia, Germany, Hungary, Iceland, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Romania, and Slovakia.

The domestic transport sector has exhibited the poorest performance among all sectors, as most countries increased their emissions. The exceptions were Sweden (– 1.1%), Switzerland (– 0.8%), the UK (– 0.6%), Finland (– 0.5%), Belgium (– 0.3%), France (– 0.2%), Germany, the Netherlands, and Norway (– 0.1%), with very modest downward values. However, signs at the end of the period shifted toward a reduction, with only six countries experiencing an increase in their emissions: Latvia, Lithuania, Poland, Romania, Slovakia, and Turkey.

Finally, emissions in the residential sector exhibit a more favorable environmental pattern, with most countries reducing emissions by the end of 2019. Notable reductions were observed in Sweden (– 6.8%), Bulgaria (– 3.3%), Denmark (– 3.3%), Latvia (– 3.2%), Czechia (– 3.0%), Lithuania, and Slovakia (– 3.0%). However, others exhibited an opposite trend, such as Iceland (2.2%), Turkey (1.9%), Romania (1.3%), Greece (1.0%), Spain (0.9%), Portugal (0.4%), and Italy (0.2%).

Therefore, the results are far from being homogeneous, especially in the energy supply and industry sectors. We also observed that some countries experienced their worst environmental behaviors in the period 2005–2019, even increasing their emissions. These are mainly in Eastern Europe (Bulgaria, Czechia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, and Turkey). However, there are also cases as Iceland and Malta, islands far from the mainland in the Atlantic and Mediterranean Sea, respectively, and finally, Germany in Central Europe. Shifting focus to the evolution GDP, the study identifies varying growth rates among European countries, with some nations experiencing rapid economic growth. The analysis also notes the heterogeneous pattern in primary energy consumption across countries.

3.2 Methodology

The data analysis emphasizes the interconnectedness of CO₂ emissions, GDP, and energy consumption, with notable variations among European countries. It also suggests the existence of breaks in the decoupling hypothesis of economic growth and energy consumption from emissions, potentially linked to intra- or inter-country events throughout the study period. The heterogeneity across countries also reflects the importance of conducting the analysis at the country level, rather than using a panel.

To assess the impact of historical events on the trends in the model's parameters, we apply the methodology proposed by Bai and Perron (1998, 2003a, b) that is a robust option, as it endogenously determines both the number and the period in which structural breaks appear. These structural breaks refer to points in time where there is a significant change in the underlying data-generating process. Unlike some other methods that require specifying the number of breaks in advance, the Bai–Perron test does not have this requirement. It adapts to the data and identifies the number of breaks as part of the testing procedure. The sequential testing approach is computationally efficient and makes the method suitable for large datasets.

As a preliminary step before employing the Bai and Perron (1998, 2003a, b) procedure for dynamic analysis with structural breaks, it is essential to analyze the time properties of each variable series. If we cannot reject the presence of unit roots in the variables, only then can we apply this methodology. The inference for unit roots relies on a specification that incorporates an intercept and a linear trend. Within this framework, we utilized the quasi-generalized least squares detrending methods (DF-GLS) proposed by Elliott et al. (1996), instead of the standard statistics proposed in the seminal paper by Dickey and Fuller (1979), which are based on ordinary least squares estimation.

The DF-GLS test, as defined by Elliott et al. (1996), enables us to choose the number of lags from several alternatives, with the default option being the maximum depending on the sample size (Schwert 2002). However, in line with the literature, we selected the number of lags using the MAIC criterion suggested by Ng and Perron (2001), considering the size of our dataset.

Additionally, we employed the KPSS statistic (Kwiatkowski et al. 1992) enhanced by the work of Hobijn et al. (2004). This enhancement includes automatic

bandwidth selection and allows the use of the quadratic spectral kernel to consider the possible presence of autocorrelation and heterogeneity in the perturbation of the specification (Andrews 1991).

Neither the DF-GLS nor the KPSS statistics account for the potential presence of breaks in the trend function. To avoid bias caused by ignoring them (see Perron 1989 in this regard), we also employed another statistic for testing the unit root null hypothesis in the presence of breaks. We chose to use the Lagrange Multiplier (LM)-type statistic proposed by Lee and Strazicich (2003). The LS statistic includes a maximum value of two breaks that may affect both the intercept and the trend.

Once we have tested the stability of the parameters, we can then apply the Bai and Perron (1998, 2003a, b) procedure to test for the presence of multiple structural breaks as long as the variables are not integrated. Unlike most of the previous literature, we have not employed a panel data approach. Our study is based on the individual analysis of the variables of each country. Due to the variety in the heterogeneity of the periods in which the different breaks appear for each country, as well as the differences in the estimated elasticities, we consider that an individual estimation for each country in the sample is much more appropriate than the use of panel data techniques.² Our starting model is a linear relationship between CO₂, GDP, and EC, with i and t being the indicators of the country and time, respectively:

$$\text{CO}_{2it} = \alpha_i + \beta_i \text{GDP}_{it} + \delta_i \text{EC}_{it} + e_{it}, i = 1, \dots, 32t = 1990, \dots, 2019 \quad (1)$$

where CO₂, EC_{it} and GDP_{it} represent the per capita emissions, the per capita energy consumption and the per capita GDP of the i -th country, respectively, with t controlling the time dimension. Finally, e is the perturbation of the model. Taking logarithms, the model is as follows:

$$\ln(\text{CO}_2)_{it} = \alpha_i + \beta_i \ln(\text{GDP}_{it}) + \delta_i \ln(\text{EC}_{it}) + e_{it}, i = 1, \dots, 32t = 1990, \dots, 2019 \quad (2)$$

Previously, we observed the significance of structural breaks in analyzing the time properties of the variables, and we acknowledge their potential impact on the relationship between these three variables. Therefore, it is recommended to consider the presence of these breaks when estimating the elasticities. To that end, we follow the methodology developed by Bai and Perron (1998, 2003a, b). Unlike some other methods that require the user to specify the number of breaks in advance, the Bai–Perron test does not have this requirement. It adapts to the data and identifies the number of breaks as part of the testing procedure. The procedure is relatively robust to certain types of model misspecification and allows for flexible modeling of the underlying data structure. This is based on the estimation of the following model, individually for each of the countries in the sample:

² Almost all studies in the existing environment-energy-growth literature use conventional panel estimation techniques which fail to take into account cross-sectional dependence across countries in the panel (Dogan and Seker 2016).

$$\ln(\text{CO}_2)_{it} = \alpha_{ij} + \beta_{ij}\ln(\text{GDP}_{it}) + \delta_{ij}\ln(\text{EC}_{it}) + v_{it}, i = 1, \dots, 32, \\ t = \text{TB}_{j-1}, \dots, \text{TB}_j, j = 1, \dots, m + 1 \quad (3)$$

where TB_j means the period where the breaks appear, with $\text{TB}_0=1990$ and $\text{TB}_{m+1}=2019$, m being the number of breaks, and v an innovation that can follow a wide range of stationary models, including the general ARMA model.

The Bai–Perron procedure involves exclusively the estimation of the above model (3), considering that the break may appear at any point in the sample. A Chow-type test is then defined in order to determine the existence of the first break. The estimation of the period where this first break occurs coincides with the period where the Chow-type statistic attains its maximum value. The presence of multiple breaks can be analyzed by using the UD_{\max} and WD_{\max} statistics, which test the null hypothesis of no structural breaks versus the presence of an unknown number of breaks. We have considered a maximum value of five breaks, subsequently applying this statistic sequentially.

Given that the Bai–Perron procedure only works correctly once regime-wise stationarity is proved, we are limited to applying it to those cases where the unit root null hypothesis has been previously rejected. Thus, the appropriate strategy is, first, the application of the unit root tests and, once stationarity is shown, then applying the Bai–Perron sequential procedure to estimate the number of breaks, combined with the repartition method of Bai (1997) to determine the periods when the breaks appear.

The decision to pursue individual estimations for each country in our sample stems from the diverse nature of the periods in which breaks occur for different countries and the variations in estimated elasticities. These considerations lead us to favor individual estimations over the application of panel data techniques. While we acknowledge the potential trade-off between the flexibility offered by the Bai and Perron methodology and the possible efficiency gains through a collective analysis, the perceived efficiency gain appears to be minimal. We evaluated pairwise correlation coefficients of residuals from the model (3) estimations for different countries. The statistic by Pesaran (2015) allows us to reject the null hypothesis of weak cross-sectional independence. Consequently, the potential efficiency gain from panel methods like SURE estimation seems marginal, if present at all. Therefore, we have opted to pursue the individual analysis.

4 Results and discussion

4.1 Unit root inference and structural breaks

The results pertaining to unit root inference are outlined in Tables 11 through 16 in Appendix B. As observed, scant evidence is found against the null hypothesis of a unit root when disregarding broken trends. However, upon incorporating the presence of breaks, limited to a maximum of 2, in the intercept and trend of the specification, the landscape changes considerably. Robust evidence against the unit

root null hypothesis emerges for most variables under consideration, with a higher count of breaks leading to a greater number of rejections of this null hypothesis.

For the per capita energy supply sector CO₂ emissions in Denmark, the presence of a unit root cannot be rejected, even in the presence of one or two breaks. A similar scenario is found for the industry sector CO₂ emissions of France, Luxembourg, and Sweden, and for domestic transport sector CO₂ emissions of Lithuania. In addition, the unit root hypothesis for residential sector CO₂ emissions is not rejected for several countries, including Austria, Belgium, Bulgaria, Denmark, Estonia, Germany, Iceland, Lithuania, Netherlands, Switzerland, and the UK. Caution is advised in interpreting the results for these countries due to the lack of evidence against the unit root in the emissions variable. Although excluding these countries from the subsequent stage of our analysis is a viable option, retaining them allows for a comparison of their results with the rest of the sample.

Concerning GDP, the presence of a unit root is robustly rejected in all countries, while for the EC variable, Malta stands as the only exception where the null hypothesis of a unit root is not rejected.

Furthermore, examination of the years around which most breaks are concentrated reveals three distinct periods. The first, circa the mid-1990s (approximately between 1993 and 1997), was marked by economic and political turbulence. The financial crisis of the early 90s dealt a heavy blow to some Western European countries integrated into the European Monetary System, resulting in adjustments to their national currencies. Speculative attacks led to withdrawals (Italy and the UK), aggressive devaluations (Ireland, Portugal, and Spain), or endurance (Belgium, Denmark, France, and the Netherlands). Simultaneously, the political collapse of the Soviet Union in 1991 and the wars in the Balkan Peninsula in the early 90s added to the geopolitical complexity.

The second group of breaks is concentrated in the early 2000s, between 2001 and 2006. The burst of the dot-com bubble and the introduction of the euro as a single European currency for some countries in 2001 resulted in economic downturns. Additionally, the common European market's expansion in 2004 to include some former Soviet states caused further economic adjustments.

Lastly, the third break is associated with the effects of the Great Recession (2008 through 2013), where the worldwide fall in GDP was the highest since the 1929 crisis. The subsequent recovery was uneven, with some countries regaining ground within a few years, while others experienced a prolonged recovery period.

These three distinct periods of breaks substantiate our initial suspicion that certain events can disrupt the stability of the interrelation of emissions, economic growth, and energy consumption in European countries.

4.2 Relationship between emissions, GDP and energy consumption by economic sector

Tables 1, 2, 3, and 4 present the results obtained through the Bai–Perron methodology, detailing the relationship between our variables across individual countries and economic sectors.

Table 1 Testing for breaks and estimation of the energy supply sector CO₂ emissions equation (GDP and EC) by individual country

	UD _{max}	WD _{max}	α_1	β_1	δ_1	TB ₁	α_2	β_2	δ_2	TB ₂	α_3	β_3	δ_3
Austria	7	8	0.45	-2.32	2.87	1993	0.33	-0.24	0.33	2012	0.54	-0.36	0.43
Belgium	10	10	0.03	0.10	0.12		0.05	0.09	0.12		0.02	0.16	0.21
			0.72	-0.19	0.26	2007	1.06	-0.62	0.75				
Bulgaria	21	21	0.03	0.03	0.04		0.01	0.06	0.07				
			1.42	0.16	-0.21	2009	1.30	-0.79	1.01				
			0.03	0.08	0.09		0.02	0.11	0.14				
Croatia	16	19	0.39	1.57	-1.93	2003	0.36	-0.24	0.33	2010	0.52	-1.25	1.63
			0.05	0.56	0.69		0.04	0.14	0.17		0.03	0.05	0.07
Cyprus	12	12	0.98	0.40	-0.47	2012	1.10	0.30	-0.40				
			0.01	0.08	0.10		0.02	0.15	0.20				
Czechia	36	42	1.84	-0.23	0.26	1994	1.78	-0.08	0.12	2006	1.89	-0.49	0.61
			0.02	0.09	0.10		0.02	0.05	0.06		0.01	0.03	0.04
Denmark	24	24	0.84	-0.59	0.84	2012	1.69	-2.04	2.66				
			0.09	0.08	0.11		0.04	0.11	0.15				
Estonia	7	7	2.28	-0.15	0.16	2005	2.23	-0.50	0.62				
			0.04	0.05	0.06		0.02	0.23	0.28				
Finland (a)	39	54	1.53	-0.87	0.97	1993	1.48	-0.87	1.01	2000	1.46	-2.64	3.12
			0.04	0.84	0.96		0.05	0.19	0.22		0.04	0.18	0.21
France (a)	10	10	-0.29	-0.33	0.45	2010	0.12	-0.78	0.96				
			0.04	0.05	0.07		0.02	0.11	0.14				
Germany	17	20	1.49	-0.67	0.83	1999	1.52	-0.12	0.15	2014	1.57	-1.21	1.57
			0.02	0.03	0.04		0.04	0.03	0.04		0.01	0.25	0.33
Greece	26	26	1.26	0.16	-0.17	2014	1.57	-0.97	1.26				
			0.04	0.09	0.12		0.01	0.32	0.43				

Table 1 (continued)

	UD _{max}	WD _{max}	α_1	β_1	δ_1	TB ₁	α_2	β_2	δ_2	TB ₂	α_3	β_3	δ_3
Hungary	44	51	0.69	0.54	-0.60	1999	0.72	-0.40	0.52	2008	0.93	-0.79	0.98
			0.04	0.07	0.08		0.05	0.05	0.07		0.01	0.06	0.08
Iceland	19	19	-0.63	0.21	-0.28	1998	-1.07	-0.71	0.83				
			0.03	0.57	0.63		0.03	0.09	0.09				
Ireland	9	11	1.11	0.68	-0.81	1999	1.15	-0.75	0.98	2014	1.24	-1.20	1.63
			0.05	0.03	0.04		0.06	0.03	0.04		0.03	0.16	0.22
Italy	5	5	0.59	-0.15	0.24	2012	0.97	-0.53	0.67				
			0.02	0.08	0.11		0.01	0.07	0.09				
Latvia	9	9	-0.01	-0.51	0.64	2009	0.12	-0.25	0.31				
			0.02	0.03	0.04		0.04	0.14	0.18				
Lithuania	37	37	0.28	-0.18	0.25	2009	0.55	-1.41	1.86				
			0.06	0.04	0.05		0.02	0.12	0.17				
Luxembourg	66	89	0.19	1.39	-1.81	1997	-0.24	-0.75	0.84	2001	-1.07	-0.61	0.96
			0.17	0.14	0.16		0.23	2.37	2.84		0.16	0.20	0.25
Malta	73	98	1.29	-0.90	1.12	1994	1.31	0.01	0.01	2000	1.16	-0.42	0.61
			0.09	0.35	0.42		0.10	0.06	0.08		0.13	0.07	0.10
Netherlands	17	20	1.39	1.04	-1.25	1996	1.35	-0.17	0.22	2013	1.40	-0.93	1.23
			0.01	0.15	0.19		0.01	0.04	0.06		0.01	0.10	0.13
Norway	33	33	1.28	0.77	-0.95	1999	1.06	-0.10	0.15				
			0.01	0.09	0.11		0.03	0.03	0.03				
Poland	9	9	1.64	-1.07	1.22	1993	1.86	-0.09	0.09				
			0.01	0.32	0.36		0.02	0.01	0.01				
Portugal	13	15	0.64	-2.13	2.72	1995	0.57	-0.53	0.70	2011	0.67	-0.82	1.09
			0.03	0.34	0.44		0.03	0.20	0.26		0.03	0.58	0.79

Table 1 (continued)

	UD _{max}	WD _{max}	α_1	β_1	δ_1	TB ₁	α_2	β_2	δ_2	TB ₂	α_3	β_3	δ_3
Romania	19	22	0.81	-0.42	0.54	1999	0.97	0.01	0.01	2008	1.16	-0.60	0.75
			0.04	0.04	0.05		0.07	0.03	0.04		0.04	0.05	0.07
Slovakia	20	23	0.70	-0.45	0.54	1997	0.66	-0.32	0.41	2009	0.92	-1.02	1.26
			0.05	0.09	0.11		0.07	0.05	0.06		0.02	0.13	0.17
Slovenia	10	10	1.02	0.26	-0.29	2008	1.18	-0.77	0.97				
			0.04	0.05	0.06		0.01	0.09	0.11				
Spain	7	9	0.76	-0.20	0.25	1995	0.64	-0.47	0.63	2013	0.83	-2.21	2.93
			0.04	0.41	0.51		0.05	0.16	0.20		0.03	0.25	0.33
Sweden (a)	7	7	0.08	-0.17	0.22	2008	0.27	-0.99	1.24				
			0.04	0.07	0.09		0.02	0.12	0.15				
Switzerland	32	32	-0.75	0.50	-0.64	2006	-0.71	-0.55	0.74				
			0.02	0.08	0.10		0.02	0.05	0.07				
Turkey	13	15	0.45	0.99	-1.42	1997	0.32	0.98	-1.30	2006	0.07	0.08	-0.04
			0.04	0.61	0.82		0.08	0.22	0.30		0.05	0.11	0.15
UK	196	263	1.08	-0.65	0.83	1998	0.93	-0.28	0.40	2012	1.15	-1.71	2.26
			0.07	0.07	0.08		0.12	0.07	0.09		0.07	0.25	0.33
	TB ₃	α_4	β_4	δ_4	TB ₄	α_5	β_5	δ_5	TB ₅	α_6	β_6	δ_6	R2
Austria													0.96
Belgium													0.96
Bulgaria													0.82
Croatia													0.93
Cyprus													0.95
Czechia													0.95

Table 1 (continued)

	TB ₃	α_4	β_4	δ_4	TB ₄	α_5	β_5	δ_5	TB ₅	α_6	β_6	δ_6	R ₂
Denmark													0.99
Estonia													0.89
Finland (a)	2005	1.58	-1.31	1.59									0.95
		0.04	0.08	0.10									
France (a)													0.91
Germany													0.95
Greece													0.95
Hungary													0.97
Iceland													0.89
Ireland													0.98
Italy													0.97
Latvia													0.88
Lithuania													0.91
Luxembourg	2013	-0.26	-5.33	6.93									0.98
		0.25	0.50	0.65									
Malta	2014	1.52	-2.16	2.94									0.99
		0.02	0.31	0.44									
Netherlands													0.90
Norway													0.94
Poland													0.91
Portugal													0.86
Romania													0.99
Slovakia													0.97
Slovenia													0.80

Table 1 (continued)

	TB ₃	α_4	β_4	δ_4	TB ₄	α_5	β_5	δ_5	TB ₅	α_6	β_6	δ_6	R ²
Spain													0.94
Sweden (a)													0.73
Switzerland													0.81
Turkey													0.97
UK	2015	1.25	-1.65	2.15									0.99
		0.03	0.01	0.02									

This table presents the results of the estimation results of model (3) with TB_j (j= 1, 2, 3, 4, 5) being the estimated periods when the break appears. The number of breaks has been selected by using the sequential procedure described in Bai and Perron (1998). UD_{max} and WD_{max} test the no structural break null hypothesis using the appropriate critical values. White–Huber robust standard deviations are presented below the estimated parameters

(a) Suppresses intercept

Table 2 Testing for breaks and estimation of the industry sector CO₂ emissions equation (GDP and EC) by individual country

	UD _{max}	WD _{max}	α_1	β_1	δ_1	TB ₁	α_2	β_2	δ_2	TB ₂	α_3	β_3	δ_3
Austria	4	5	1.13	-1.16	1.42	1993	1.13	-0.09	0.12	1999	1.12	-0.01	0.01
	28	28	0.01	0.07	0.90		0.01	0.24	0.30		0.01	0.50	0.63
Belgium			1.13	-0.29	0.39	2008	1.54	-0.18	0.18				
	24	31	0.01	0.02	0.03		0.01	0.08	0.11				
Bulgaria			0.39	-0.49	0.63	1997	0.49	0.02	-0.01	2008	0.76	1.13	-1.50
	17	17	0.05	0.45	0.51		0.10	0.13	0.15		0.04	0.15	0.19
Croatia			0.24	0.84	-1.04	2008	0.36	-0.41	0.53				
	19	25	0.02	0.12	0.15		0.04	0.11	0.15				
Cyprus			0.51	-0.57	0.68	1993	0.49	-0.45	0.54	2003	0.55	-1.28	1.57
	19	22	0.03	3.70	4.31		0.03	0.11	0.13		0.02	0.18	0.23
Czechia			1.10	-1.28	1.51	1993	1.15	-1.15	1.35	1999	1.17	-1.34	1.60
	64	75	0.03	0.63	0.71		0.06	0.07	0.08		0.05	0.31	0.37
Denmark			0.22	0.32	-0.36	2000	0.28	-0.71	0.92	2008	0.49	-0.24	0.27
	8	9	0.05	0.06	0.08		0.05	0.07	0.09		0.01	0.03	0.05
Estonia			0.10	-0.02	0.05	2008	0.23	0.98	-1.19	2014	0.28	0.18	-0.26
	21	21	0.05	0.09	0.10		0.04	0.41	0.50		0.03	0.10	0.12
Finland			0.91	-0.01	0.04	2008	1.24	-0.76	0.90				
	17	17	0.03	0.03	0.04		0.01	0.07	0.09				
France			0.45	-0.43	0.56	2008	0.81	-0.35	0.41				
	41	44	0.01	0.04	0.04		0.01	0.03	0.05				
Germany			0.84	-0.80	1.00	2002	0.93	0.21	-0.28	2008	0.98	0.06	-0.09
	19	22	0.01	0.03	0.03		0.03	0.05	0.07		0.02	0.05	0.07
Greece			0.65	-0.69	0.87	1994	0.53	-0.59	0.78	2010	0.74	0.25	-0.37
			0.03	0.08	0.10		0.03	0.12	0.15		0.02	0.17	0.23

Table 2 (continued)

	UD _{max}	WD _{max}	α_1	β_1	δ_1	TB ₁	α_2	β_2	δ_2	TB ₂	α_3	β_3	δ_3
Hungary	37	43	0.16	-0.64	0.79	1996	0.22	-0.09	0.11	2008	0.32	0.77	-1.03
			0.02	0.37	0.43		0.05	0.07	0.08		0.03	0.12	0.16
Iceland	11	12	1.69	-2.17	2.37	1993	1.73	-0.51	0.53	2000	1.64	-1.40	1.57
			0.04	0.37	0.40		0.04	0.88	0.98		0.05	0.24	0.27
Ireland	35	35	0.42	0.04	-0.01	2008	0.77	0.15	-0.25				
			0.02	0.05	0.07		0.01	0.05	0.07				
Italy	16	18	0.44	-0.06	0.13	2008	0.71	-0.12	0.14	2012	0.78	-0.15	0.15
			0.03	0.08	0.10		0.04	0.28	0.37		0.02	0.07	0.10
Latvia	8	8	-0.21	-0.20	0.23	2009	-0.32	-0.41	0.55				
			0.03	0.07	0.08		0.03	0.16	0.21				
Lithuania	16	16	0.41	0.60	-0.72	2008	0.35	0.51	-0.67				
			0.04	0.09	0.10		0.06	0.07	0.10				
Luxembourg	196	264	1.47	-1.01	1.31	1994	1.65	-3.09	3.72	1999	1.77	-0.07	0.06
			0.07	0.05	0.06		0.13	0.57	0.67		0.16	0.10	0.13
Malta	43	57	-0.99	0.39	-0.55	1996	-0.95	-0.15	0.11	2005	-1.21	1.82	-2.35
			0.11	0.11	0.14		0.12	0.19	0.24		0.12	0.34	0.45
Netherlands	20	24	0.89	-0.22	0.32	1998	1.01	-0.40	0.51	2007	1.17	-0.17	0.18
			0.03	0.07	0.08		0.06	0.12	0.15		0.03	0.05	0.07
Norway	44	67	1.09	-4.16	4.91	1993	1.05	-0.11	0.17	2001	1.11	-0.26	0.33
			0.04	0.21	0.25		0.04	0.04	0.04		0.04	0.04	0.06
Poland	28	33	0.46	1.03	-1.14	1995	0.43	-0.44	0.55	2008	0.55	0.14	-0.20
			0.02	0.28	0.31		0.03	0.08	0.10		0.03	0.09	0.12
Portugal	6	6	0.37	0.10	-0.11	2008	0.54	-0.06	0.06				
			0.01	0.09	0.12		0.01	0.11	0.15				

Table 2 (continued)

	UD _{max}	WD _{max}	α_1	β_1	δ_1	TB ₁	α_2	β_2	δ_2	TB ₂	α_3	β_3	δ_3
Romania	10	10	0.45	-1.54	1.80	1998	0.95	-0.20	0.19				
			0.03	0.14	0.16		0.08	0.03	0.04				
Slovakia (a)	8	8	1.14	-0.20	0.25	2005	1.29	-0.38	0.47				
			0.02	0.03	0.03		0.01	0.04	0.05				
Slovenia	13	15	0.45	-2.24	2.68	1996	0.44	0.28	-0.33	2008	0.60	0.03	-0.07
			0.03	0.78	0.93		0.04	0.08	0.10		0.01	0.07	0.09
Spain	6	6	0.43	-0.32	0.45	2014	0.76	0.10	-0.18				
			0.01	0.09	0.12		0.03	0.07	0.09				
Sweden	8	8	0.41	-0.07	0.13	2008	0.75	-0.46	0.54				
			0.02	0.05	0.06		0.01	0.13	0.17				
Switzerland	25	29	0.25	-1.67	2.11	1993	0.22	0.08	-0.09	2008	0.32	-0.47	0.63
			0.01	0.18	0.23		0.03	0.02	0.03		0.01	0.07	0.10
Turkey	7	7	0.35	-0.40	0.51	2007	0.24	0.63	-0.85				
			0.02	0.17	0.23		0.03	0.17	0.24				
UK	11	11	0.28	-0.62	0.83	2008	0.75	-0.37	0.44				
			0.02	0.05	0.06		0.03	0.02	0.03				
	TB ₃	α_4	β_4	δ_4	TB ₄	α_5	β_5	δ_5	TB ₅	α_6	β_6	δ_6	R2
Austria	2003	1.11	0.27	-0.33	2008	1.12	-0.02	0.02	2012	1.12	-0.15	0.20	0.83
		0.01	0.08	0.11		0.01	0.21	0.28		0.01	0.05	0.06	
Belgium													0.97
Bulgaria													0.98
Croatia													0.93
Cyprus	2012	0.56	-0.66	0.83									0.86

Table 2 (continued)

	TB ₃	α_4	β_4	δ_4	TB ₄	α_5	β_5	δ_5	TB ₅	α_6	β_6	δ_6	R2
Czechia	2003	0.03	0.23	0.29		1.33	-0.12	0.10					0.99
		1.18	-0.40	0.48	2009	0.04	0.05	0.06					
		0.06	0.08	0.09									
Denmark													0.99
Estonia													0.79
Finland													0.96
France													0.98
Germany													0.96
Greece													0.93
Hungary													0.96
Iceland	2008	1.54	-0.13	0.18									0.91
		0.05	0.07	0.08									
Ireland													0.95
Italy													0.99
Latvia													0.77
Lithuania													0.82
Luxembourg	2007	2.05	-0.45	0.48									0.99
		0.14	0.04	0.06									
		-1.37	-0.02	0.16									
Malta	2012	0.07	0.09	0.12									0.98
Netherlands													0.97
Norway	2007	1.15	0.01	-0.04	2011	1.22	-0.27	0.31					0.97
		0.04	0.21	0.27		0.03	0.02	0.03					0.89
Poland													0.89
Portugal													0.89

Table 2 (continued)

	TB ₃	α_4	β_4	δ_4	TB ₄	α_5	β_5	δ_5	TB ₅	α_6	β_6	δ_6	R ²
Romania													0.93
Slovakia (a)													0.88
Slovenia													0.92
Spain													0.97
Sweden													0.96
Switzerland													0.95
Turkey													0.73
UK													0.98

This table presents the results of the estimation results of model (3) with TB_j ($j=1, 2, 3, 4, 5$) being the estimated periods when the break appears. The number of breaks has been selected by using the sequential procedure described in Bai and Perron (1998). UD_{max} and WD_{max} test the no structural break null hypothesis using the appropriate critical values. White–Huber robust standard deviations are presented below the estimated parameters

(a) Suppresses intercept

Table 3 Testing for breaks and estimation of the domestic transport sector CO₂ emissions equation (GDP and EC) by individual country

	UD _{mx}	WD _{mx}	α_1	β_1	δ_1	TB ₁	α_2	β_2	δ_2	TB ₂	α_3	β_3	δ_3
Austria	15	17	1.01	0.87	-1.11	2001	0.85	-0.39	0.52	2009	0.86	0.10	-0.12
			0.01	0.19	0.24		0.03	0.09	0.12		0.03	0.05	0.07
Belgium	38	44	0.84	0.33	-0.39	2008	0.86	-0.32	0.40	2014	0.86	-0.23	0.30
			0.01	0.03	0.03		0.01	0.06	0.08		0.01	0.07	0.10
Bulgaria	62	62	-0.08	-2.53	2.78	1993	-0.04	0.22	-0.31	2000	-0.16	1.31	-1.53
			0.06	0.31	0.34		0.07	0.61	0.69		0.08	0.11	0.13
Croatia	5	5	0.28	-2.82	3.39	1998	-0.17	0.38	-0.43				
			0.03	2.15	2.64		0.04	0.05	0.06				
Cyprus	12	14	0.65	0.60	-0.71	1999	0.56	0.05	-0.05	2012	0.65	0.42	-0.56
			0.02	0.14	0.17		0.01	0.07	0.08		0.01	0.12	0.16
Czechia	17	20	0.43	-0.06	0.03	1997	0.29	0.80	-0.95	2009	0.24	0.28	-0.33
			0.03	0.10	0.11		0.05	0.14	0.17		0.05	0.05	0.06
Denmark	18	18	0.82	0.18	-0.22	2009	0.86	-0.06	0.08				
			0.01	0.03	0.03		0.01	0.05	0.06				
Estonia	14	14	0.48	1.06	-1.18	1997	0.43	0.44	-0.52	2002	0.38	0.45	-0.52
			0.02	0.40	0.43		0.04	0.17	0.19		0.04	0.06	0.07
Finland	5	5	0.79	0.18	-0.20	2006	0.85	-0.41	0.49				
			0.02	0.04	0.05		0.01	0.05	0.06				
France	51	59	0.75	0.34	-0.41	1999	0.74	-0.24	0.31	2007	0.81	-0.10	0.12
			0.01	0.02	0.03		0.01	0.01	0.02		0.01	0.01	0.01
Germany	39	46	0.69	0.16	-0.19	1998	0.70	-0.80	1.00	2006	0.75	0.12	-0.17
			0.01	0.01	0.02		0.01	0.05	0.06		0.01	0.02	0.03
Greece	14	14	0.45	0.63	-0.79	2011	0.57	0.24	-0.33				
			0.01	0.08	0.10		0.02	0.05	0.07				

Table 3 (continued)

	UD _{mx}	WD _{mx}	α_1	β_1	δ_1	TB ₁	α_2	β_2	δ_2	TB ₂	α_3	β_3	δ_3
Hungary	22	22	0.19	0.72	-0.91	2009	-0.06	0.63	-0.79				
			0.03	0.05	0.06		0.05	0.23	0.30				
Iceland	33	45	1.02	-0.18	0.18	2002	0.93	-0.39	0.45	2006	0.93	0.88	-0.95
			0.01	0.07	0.08		0.02	0.41	0.46		0.01	0.07	0.08
Ireland	33	33	0.90	0.89	-1.13	2009	0.85	0.03	-0.04				
			0.01	0.09	0.11		0.06	0.03	0.04				
Italy	12	14	0.63	1.12	-1.42	2004	0.67	-0.57	0.76	2013	0.71	-0.06	0.06
			0.02	0.89	0.11		0.02	0.08	0.11		0.01	0.10	0.14
Latvia	33	38	0.36	-0.03	-0.02	1999	0.22	0.95	-1.19	2010	0.15	0.84	-1.07
			0.03	0.01	0.01		0.08	0.13	0.17		0.07	0.08	0.11
Lithuania	12	12	0.39	-0.02	-0.01	2000	-0.01	0.42	-0.49				
			0.05	0.16	0.19		0.03	0.04	0.05				
Luxembourg	75	88	2.46	0.13	-0.19	1997	2.25	0.25	-0.28	2010	2.37	-0.63	0.82
			0.03	0.15	0.17		0.04	0.23	0.28		0.05	0.05	0.07
Malta	18	18	0.30	0.48	-0.60	2000	0.19	0.09	-0.10				
			0.01	0.09	0.11		0.04	0.03	0.04				
Netherlands	9	9	0.60	0.11	-0.12	2011	0.72	-0.23	0.29				
			0.01	0.02	0.03		0.01	0.08	0.11				
Norway	19	23	1.03	0.36	-0.44	1996	0.91	0.07	-0.07	2014	1.01	-0.71	0.91
			0.01	0.04	0.05		0.01	0.02	0.03		0.01	0.10	0.13
Poland	10	12	0.12	0.63	-0.80	1999	-0.05	1.19	-1.47	2009	-0.25	0.65	-0.77
			0.06	0.04	0.04		0.09	0.12	0.15		0.05	0.23	0.29
Portugal	8	11	0.53	-1.79	2.25	1993	0.50	-1.94	2.46	1999	0.39	-0.24	0.34
			0.02	0.66	0.85		0.03	0.86	1.10		0.03	0.04	0.06

Table 3 (continued)

	UD _{mx}	WD _{mx}	α_1	β_1	δ_1	TB ₁	α_2	β_2	δ_2	TB ₂	α_3	β_3	δ_3
Romania	10	10	-0.40	-0.93	0.98	1995	-0.82	0.32	-0.36				
			0.04	0.14	0.15		0.05	0.03	0.04				
Slovakia (a)	11	11	0.30	0.34	-0.42	2004	0.06	-0.02	0.06				
			0.01	0.05	0.06		0.02	0.06	0.08				
Slovenia	20	24	0.87	6.83	-8.15	1997	0.82	0.59	-0.74	2006	0.62	0.03	0.01
			0.03	1.38	1.64		0.06	0.19	0.23		0.04	0.08	0.11
Spain	13	15	0.70	1.61	-2.03	1996	0.56	0.01	0.01	2010	0.69	0.35	-0.48
			0.02	0.68	0.85		0.01	0.12	0.15		0.03	0.13	0.17
Sweden	109	109	0.65	0.08	-0.07	2007	0.81	-0.76	0.95				
			0.03	0.01	0.01		0.01	0.04	0.06				
Switzerland	35	40	0.70	-0.36	0.46	1998	0.69	-0.07	0.10	2011	0.75	-0.61	0.83
			0.01	0.12	0.15		0.02	0.02	0.03		0.01	0.11	0.15
Turkey	12	12	-0.12	-0.05	0.01	2009	-0.54	1.91	-2.55				
			0.05	0.17	0.22		0.02	0.84	1.15				
UK	13	13	0.61	-0.09	0.13	2009	0.77	-0.06	0.07				
			0.01	0.04	0.05		0.01	0.02	0.03				
	TB ₃	α_4	β_4	δ_4	TB ₄	α_5	β_5	δ_5	TB ₅	α_6	β_6	δ_6	R2
Austria													0.97
Belgium													0.91
Bulgaria	2005	-0.22	0.04	-0.01	2011	-0.21	-0.29	0.41	2015	-0.23	0.48	-0.54	0.96
		0.08	0.03	0.04		0.07	0.57	0.71		0.07	0.05	0.06	
Croatia													0.99
Cyprus													0.96
Czechia													0.97

Table 3 (continued)

	TB ₃	α_4	β_4	δ_4	TB ₄	α_5	β_5	δ_5	TB ₅	α_6	β_6	δ_6	R ₂
Denmark													0.91
Estonia	2007	0.28	0.13	-0.12									0.95
Finland													0.75
France													0.98
Germany													0.95
Greece													0.93
Hungary													0.97
Iceland	2011	0.93	0.36	-0.40									0.91
Ireland													0.98
Italy													0.96
Latvia													0.98
Lithuania													0.97
Luxembourg													0.98
Malta													0.86
Netherlands													0.92
Norway													0.93
Poland													0.98
Portugal	2011	0.49	0.54	-0.74									0.98
Romania													0.94
Slovakia (a)													0.89
Slovenia													0.95

Table 3 (continued)

	TB ₃	α_4	β_4	δ_4	TB ₄	α_5	β_5	δ_5	TB ₅	α_6	β_6	δ_6	R ²
Spain													0.98
Sweden													0.97
Switzerland													0.88
Turkey													0.95
UK													0.97

This table presents the results of the estimation results of model (3) with TB_j ($j=1, 2, 3, 4, 5$) being the estimated periods when the break appears. The number of breaks has been selected by using the sequential procedure described in Bai and Perron (1998). UD_{max} and WD_{max} test the no structural break null hypothesis using the appropriate critical values. White–Huber robust standard deviations are presented below the estimated parameters

(a) Suppresses intercept

Table 4 Testing for breaks and estimation of the residential sector CO₂ emissions equation (GDP and EC) by individual country

	UD _{max}	WD _{max}	α_1	β_1	δ_1	TB ₁	α_2	β_2	δ_2	TB ₂	α_3	β_3	δ_3
Austria	13	15	0.21	-0.48	0.63	1998	0.25	-1.10	1.42	2009	0.46	-0.62	0.76
Belgium (a)	12	12	0.05	0.19	0.23		0.06	0.06	0.08		0.02	0.10	0.13
			0.88	0.28	-0.32	1995	1.00	-0.45	0.55				
			0.03	0.29	0.34		0.01	0.02	0.03				
Bulgaria	20	24	-1.43	-1.35	1.64	1995	-1.30	-0.81	0.94	1999	-0.74	-0.12	0.05
			0.05	0.33	0.37		0.08	1.29	1.45		0.09	0.08	0.09
Croatia	39	61	-0.36	1.07	-1.33	1998	-0.42	0.86	-1.05	2005	-0.39	-0.18	0.24
			0.02	1.42	1.74		0.02	0.08	0.11		0.03	0.26	0.33
Cyprus	13	13	-0.68	0.65	-0.74	1998	-0.49	-0.71	0.86				
			0.04	0.25	0.30		0.02	0.04	0.05				
Czechia	22	22	0.30	-0.90	1.09	1995	0.42	-0.64	0.76	2008	0.54	-0.27	0.30
			0.03	0.26	0.30		0.08	0.08	0.09		0.05	0.07	0.09
Denmark	7	7	-0.59	-0.63	0.87	2011	0.05	-0.80	1.01				
			0.04	0.02	0.02		0.04	0.08	0.11				
Estonia	8	8	-0.81	2.26	-2.42	1996	-0.87	-0.05	0.07				
			0.01	1.05	1.12		0.07	0.02	0.03				
Finland	9	10	-0.08	0.78	-0.84	1993	-0.13	-0.23	0.30	2005	0.17	-0.83	0.97
			0.04	0.41	0.47		0.06	0.05	0.06		0.02	0.05	0.07
France (a)	3	3	0.07	-0.24	0.34	2010	0.38	-0.60	0.74				
			0.03	0.04	0.05		0.01	0.10	0.13				
Germany (a)	7	7	0.49	-0.49	0.64	2003	0.83	-0.39	0.46				
			0.02	0.05	0.07		0.02	0.05	0.06				
Greece	5	5	-0.57	1.08	-1.33	2010	-0.26	-1.43	1.86				
			0.07	0.28	0.35		0.05	0.36	0.48				

Table 4 (continued)

	UD _{max}	WD _{max}	α_1	β_1	δ_1	TB ₁	α_2	β_2	δ_2	TB ₂	α_3	β_3	δ_3
Hungary	15	21	0.25	-1.19	1.42	1998	0.28	0.47	-0.57	2004	0.29	-1.28	1.61
Iceland	18	18	0.03	0.16	0.18		0.03	0.10	0.12		0.03	0.19	0.23
Ireland	6	6	-2.99	-0.46	0.62	2003	-2.05	1.00	-1.21				
			0.17	0.67	0.74		0.04	1.18	1.29				
Ireland	6	6	0.70	-0.26	0.35	2002	0.89	-0.36	0.46				
			0.03	0.06	0.08		0.01	0.03	0.04				
Italy	9	11	0.28	-1.13	1.43	1994	0.25	0.31	-0.40	2008	0.27	-0.41	0.55
			0.01	0.43	0.55		0.01	0.11	0.15		0.01	0.07	0.10
Latvia	26	30	-0.61	-0.84	0.97	1998	-0.58	0.52	-0.66	2007	-0.63	-0.32	0.42
			0.01	0.12	0.14		0.01	0.09	0.11		0.03	0.05	0.07
Lithuania	68	79	-0.94	-1.14	1.32	1999	-0.83	0.41	-0.54	2011	-0.96	0.23	-0.29
			0.03	0.23	0.26		0.03	0.03	0.04		0.04	0.19	0.26
Luxembourg	7	7	1.07	-0.01	0.03	2004	1.30	-0.28	0.33				
			0.02	0.05	0.06		0.01	0.03	0.04				
Malta	24	33	-1.19	0.10	0.01	2000	-0.85	-0.31	0.42	2004	-0.65	-0.34	0.35
			0.06	0.10	0.13		0.11	0.03	0.04		0.10	0.33	0.43
Netherlands	12	14	0.46	-0.34	0.44	2007	0.60	-1.92	2.47	2011	0.67	-0.77	0.99
			0.03	0.06	0.07		0.03	0.18	0.23		0.02	0.15	0.20
Norway	9	9	-0.69	0.26	-0.26	1999	-0.27	-0.72	0.87				
			0.04	0.21	0.25		0.02	0.09	0.12				
Poland	11	15	0.18	1.30	-1.42	1993	0.22	-0.76	0.88	2001	0.21	0.38	-0.47
			0.02	0.79	0.89		0.02	0.08	0.09		0.03	0.04	0.06
Portugal	19	22	-1.02	1.44	-1.82	2005	-0.93	-1.23	1.63	2013	-0.88	0.07	-0.13
			0.03	1.04	1.34		0.04	0.11	0.15		0.04	0.06	0.08

Table 4 (continued)

	UD _{max}	WD _{max}	α_1	β_1	δ_1	TB ₁	α_2	β_2	δ_2	TB ₂	α_3	β_3	δ_3
Romania	17	20	-0.72	-1.44	1.56	1996	-0.80	0.52	-0.62	2006	-0.91	0.05	-0.03
Slovakia	5	5	-0.03	-0.53	0.65	2005	0.28	-0.61	0.74		0.05	0.07	0.10
Slovenia	15	15	0.03	0.09	0.11		0.04	0.08	0.10				
			-0.11	2.50	-2.95	1999	0.12	-1.29	1.60				
Spain	13	13	0.08	0.33	0.39		0.07	0.06	0.08				
			-0.45	0.85	-1.09	2008	-0.51	-0.68	0.91				
Sweden	14	16	0.02	0.21	0.27		0.03	0.14	0.19				
			-1.28	-1.07	1.40	2000	-0.74	-2.04	2.48	2011	-0.46	-1.11	1.26
			0.12	0.18	0.21		0.21	0.10	0.12		0.12	0.11	0.14
Switzerland	11	13	0.46	-0.40	0.56	2009	0.75	-1.25	1.67	2014	0.78	-1.02	1.35
			0.04	0.03	0.04		0.04	0.09	0.12		0.03	0.78	1.07
Turkey	15	15	-0.32	0.73	-1.04	2007	-0.76	-0.44	0.67				
			0.01	0.17	0.23		0.03	0.19	0.26				
UK	16	18	0.38	-0.26	0.35	2006	0.51	-0.33	0.43	2009	0.62	-0.42	0.53
			0.03	0.07	0.08		0.03	0.22	0.28		0.02	0.10	0.14
	TB ₃	α_4	β_4	δ_4	TB ₄	α_5	β_5	δ_5	TB ₅	α_6	β_6	δ_6	R2
Austria													0.98
Belgium (a)													0.92
Bulgaria													0.92
Croatia	2010	-0.34	-0.79	1.03	2016	-0.36	-0.58	0.77					0.94
		0.02	0.26	0.34		0.02	0.04	0.06					
Cyprus													0.93
Czechia													0.96

Table 4 (continued)

	TB ₃	α_4	β_4	δ_4	TB ₄	α_5	β_5	δ_5	TB ₅	α_6	β_6	δ_6	R2
Denmark													0.99
Estonia													0.41
Finland													0.98
France (a)													0.94
Germany (a)													0.95
Greece													0.93
Hungary	2008	0.39	-0.48	0.60									0.96
		0.02	0.09	0.11									
Iceland													0.71
Ireland													0.93
Italy													0.84
Latvia													0.93
Lithuania													0.88
Luxembourg													0.87
Malta	2011	-0.67	-0.12	0.10									0.96
		0.12	0.11	0.15									
Netherlands													0.96
Norway													0.90
Poland	2009	0.20	-0.59	0.78									0.88
		0.03	0.08	0.11									
Portugal													0.97
Romania													0.89
Slovakia													0.92
Slovenia													0.93

Table 4 (continued)

	TB ₃	α_4	β_4	δ_4	TB ₄	α_5	β_5	δ_5	TB ₅	α_6	β_6	δ_6	R ²
Spain													0.91
Sweden													0.99
Switzerland													0.95
Turkey													0.91
UK													0.98

This table presents the results of the estimation results of model (3) with TB_j (j = 1, 2, 3, 4, 5) being the estimated periods when the break appears. The number of breaks has been selected by using the sequential procedure described in Bai and Perron (1998). UD_{max} and WD_{max} test the no structural break null hypothesis using the appropriate critical values. White–Huber robust standard deviations are presented below the estimated parameters

(a) Suppresses intercept

These tables furnish statistical information crucial for scrutinizing the null hypothesis of no structural breaks in Eq. (3). Additionally, they display the estimated parameters along with their corresponding White–Huber robust standard deviations, the count of breaks, and the periods during which these breaks occur. The tables culminate with a statistical analysis assessing the quality of the estimation.³

We extend our analysis to identify behavioral patterns among country clusters in Europe and economic sectors, as presented in Tables 5, 6, 7, and 8. We highlight the significance of shared cultural values and similar historical legacies in defining peer countries with analogous background characteristics. Accordingly, geographic proximity serves as the cornerstone for grouping countries into regions. Therefore, we delineate five distinct geographic regions in Europe: Central, Eastern, Northern, Southern, and Western. Central Europe encompasses Czechia, Hungary, Poland, Slovakia, and Slovenia. The Eastern region comprises Bulgaria, Croatia, Estonia, Latvia, Lithuania, Romania, and Turkey. Northern Europe consists of Denmark, Finland, Iceland, Norway, and Sweden. The countries of Cyprus, Greece, Italy, Malta, Portugal, and Spain are situated in the Southern region of Europe. Lastly, the Western region is comprised of Austria, Belgium, France, Germany, Ireland, Luxembourg, the Netherlands, Switzerland, and the UK.

Considering the outcomes of the UD_{\max} and WD_{\max} statistics, we can confidently reject the null hypothesis of non-structural breaks. The varying number of breaks for each country underscores the necessity of analyzing each country separately rather than resorting to panel data. Notably, the breaks tend to cluster around the periods identified in the univariate analysis. The first two periods shed light on the third period, with the economic repercussions of the Great Recession accounting for over one-third of the total breakdowns. Moreover, every country exhibits at least one break related to this period. Conversely, only Denmark, France, Ireland, Lithuania, and Sweden show no breaks associated with the first period, and fewer countries exhibit zero ruptures in the second period, namely Denmark, Greece, Lithuania, and Spain.

The provided tables also allow for an examination of the estimated elasticities. The parameters β_j and δ_j denote the elasticity within each estimated subperiod concerning the relationship of GDP and EC with respect to CO₂ emissions, respectively. Figures 2, 3, 4, and 5 present maps illustrating the estimated elasticities by country at the commencement and conclusion of the considered period, spanning from 1990 to 2019. Our findings reveal pronounced heterogeneity in elasticity across countries, indicating significant changes over time.

In alignment with the decoupling hypothesis, we categorize these elasticities into three groups. First, if there is a shift in the trend in the growth rate of GDP and/or EC from the CO₂ emissions rate, the estimated parameter will be less than or equal to zero: absolute decoupling. Second, if the growth rate of CO₂ emissions is below

³ The DW statistic proposed in Durbin and Watson (1950) and the LM1 statistic for first-order autocorrelation in Breusch and Godfrey (1981) have also been used to check the goodness of estimation. As before, the results are not provided here for reasons of space, but they can be obtained from the authors upon request.

Table 5 Testing for breaks and estimation of the energy supply sector CO₂ emissions equation (GDP and EC) by geographic region

	UD _{max}	WD _{max}	α_1	β_1	δ_1	TB ₁	α_2	β_2	δ_2	TB ₂	α_3	β_3	δ_3	TB ₃	α_4	β_4	δ_4	TB ₄	α_5	β_5	δ_5	TB ₅	R ₂	
Central	30	30	2.84	-0.03	0.06	2006	3.02	-0.55	0.66															0.98
			0.02	0.01	0.02		0.01	0.02	0.03															
Eastern	20	23	3.07	-0.01	0.02	2009	3.06	-0.35	0.44	2014	3.10	-1.20	1.50											0.90
			0.03	0.05	0.06		0.02	0.08	0.10		0.01	0.29	0.36											
Northern	14	17	2.63	1.78	-2.01	1996	2.63	-0.05	0.07	2002	2.75	-1.48	1.73											0.86
			0.04	0.72	0.81		0.04	0.38	0.44		0.02	0.08	0.09											
Southern	33	38	2.89	-0.17	0.21	1997	2.77	-0.32	0.42	2014	2.95	-1.04	1.30											0.98
			0.04	0.17	0.21		0.04	0.10	0.12		0.01	0.19	0.25											
Western	35	41	3.05	0.01	0.01	2001	3.00	-0.51	0.64	2014	3.15	-1.35	1.67											0.99
			0.04	0.08	0.09		0.05	0.03	0.04		0.02	0.06	0.08											

This table presents the results of the estimation results of model (3) with TB_j (j= 1, 2, 3, 4, 5) being the estimated periods when the break appears. The number of breaks has been selected by using the sequential procedure described in Bai and Perron (1998). UD_{max} and WD_{max} test the no structural break null hypothesis using the appropriate critical values. White-Huber robust standard deviations are presented below the estimated parameters

Table 6 Testing for breaks and estimation of the industry sector CO₂ emissions equation (GDP and EC) by geographic region

	UD _{max}	WD _{max}	α_1	β_1	δ_1	TB ₁	α_2	β_2	δ_2	TB ₂	α_3	β_3
Central	13	15	2.32	-0.48	0.58	2000	2.39	-0.18	0.22	2009	2.49	0.01
			0.02	0.06	0.07		0.04	0.14	0.16		0.02	0.06
Eastern	9	9	2.16	0.11	-0.11	2008	2.33	0.20	-0.26			
			0.01	0.09	0.10		0.02	0.10	0.13			
Northern	32	43	2.70	-2.35	2.65	1993	2.70	0.87	-0.99	1999	2.67	0.09
			0.01	0.24	0.27		0.01	0.14	0.17		0.01	0.22
Southern	24	29	2.23	0.70	-0.83	2000	2.25	-0.68	0.85	2012	2.31	-0.12
			0.03	0.06	0.07		0.02	0.11	0.13		0.02	0.10
Western	37	44	3.10	-1.20	1.44	1997	3.08	-0.29	0.36	2008	3.28	-0.17
			0.03	0.21	0.25		0.06	0.03	0.04		0.03	0.03
	δ_3	TB ₃	α_4	β_4	δ_4	TB ₄	α_5	β_5	δ_5	TB ₅	R2	
Central	-0.02										0.97	
	0.08											
Eastern											0.84	
Northern	-0.10	2008	2.74	-0.36	0.41						0.93	
	0.25		0.01	0.03	0.04							
Southern	0.13										0.94	
	0.13											
Western	0.18										0.99	
	0.04											

This table presents the results of the estimation results of model (3) with TB_j ($j=1, 2, 3, 4, 5$) being the estimated periods when the break appears. The number of breaks has been selected by using the sequential procedure described in Bai and Perron (1998). UD_{max} and WD_{max} test the no structural break null hypothesis using the appropriate critical values. White–Huber robust standard deviations are presented below the estimated parameters

that of GDP and/or EC, the estimated parameter will fall between zero and one: relative decoupling. Conversely, an estimated parameter exceeding one indicates that the CO₂ emissions rate grows more rapidly than the GDP and/or EC rate: coupling. It is crucial to note that the evolution of the decoupling hypothesis for each economic sector unveils distinct realities.

4.2.1 Energy supply sector

The alterations observed in the relationship between energy supply emissions and GDP predominantly result in a reduction in elasticity for the energy supply sector. This implies that, for the most part, countries have successfully decoupled their economic growth from energy supply emissions, except for Cyprus and Turkey, which only exhibit relative decoupling. Notably, Northern European countries, which initially had values well above one, have demonstrated a remarkable transformation,

Table 7 Testing for breaks and estimation of the domestic transport sector CO₂ emissions equation (GDP and EC) by geographic region

	UD _{max}	WD _{max}	α_1	β_1	δ_1	TB ₁	α_2	β_2	δ_2	TB ₂	α_3	β_3	δ_3	TB ₃	α_4	β_4	δ_4	TB ₄	α_5	β_5	δ_5	TB ₅	R ₂	
Central	10	12	2.03	0.69	-0.82	1999	1.92	0.76	-0.90	2009	1.83	0.35	-0.40											0.99
			0.03	0.11	0.13		0.05	0.12	0.14		0.04	0.09	0.11											
Eastern	19	22	2.13	0.53	-0.65	1999	2.06	0.58	-0.69	2010	1.93	0.70	-0.85											0.99
			0.03	0.27	0.31		0.07	0.09	0.11		0.05	0.09	0.11											
Northern	31	37	2.50	0.16	-0.19	2002	2.47	0.35	-0.40	2008	2.50	-0.30	0.36											0.92
			0.01	0.02	0.02		0.01	0.10	0.11		0.01	0.03	0.03											
Southern	17	20	2.38	1.32	-1.59	1999	2.28	-0.06	0.10	2011	2.36	0.17	-0.22											0.98
			0.01	0.12	0.14		0.01	0.07	0.08		0.02	0.07	0.09											
Western	16	16	3.39	0.86	-1.03	2003	3.34	-0.35	0.44															0.97
			0.02	0.07	0.08		0.03	0.02	0.02															

This table presents the results of the estimation of model (3) with TB_j (j=1, 2, 3, 4, 5) being the estimated periods when the break appears. The number of breaks has been selected by using the sequential procedure described in Bai and Perron (1998). UD_{max} and WD_{max} test the no structural break null hypothesis using the appropriate critical values. White-Huber robust standard deviations are presented below the estimated parameters

Table 8 Testing for breaks and estimation of the residential sector CO₂ emissions equation (GDP and EC) by geographic region

	UD _{max}	WD _{max}	α_1	β_1	δ_1	TB ₁	α_2	β_2	δ_2	TB ₂	α_3	β_3	δ_3	TB ₃	α_4	β_4	δ_4	TB ₄	α_5	β_5	δ_5	TB ₅	R ₂
Central	8	8	1.65	-0.33	0.41	2008	1.92	-0.61	0.73														0.97
Eastern	8	8	0.03	0.03	0.03	2008	0.02	0.06	0.08														0.81
Northern	38	52	0.75	-0.92	1.12	2005	1.11	-1.26	1.46	2009	1.19	-1.81	2.09	2015	1.18	-0.63	0.69						0.99
Southern	6	6	0.05	0.03	0.04	2005	0.07	3.79	4.43		0.07	0.19	0.22		0.06	0.10	0.12						0.95
Western	4	4	2.73	-0.39	0.49	2007	2.99	-0.49	0.59														0.97
			0.03	0.08	0.09		0.01	0.05	0.06														

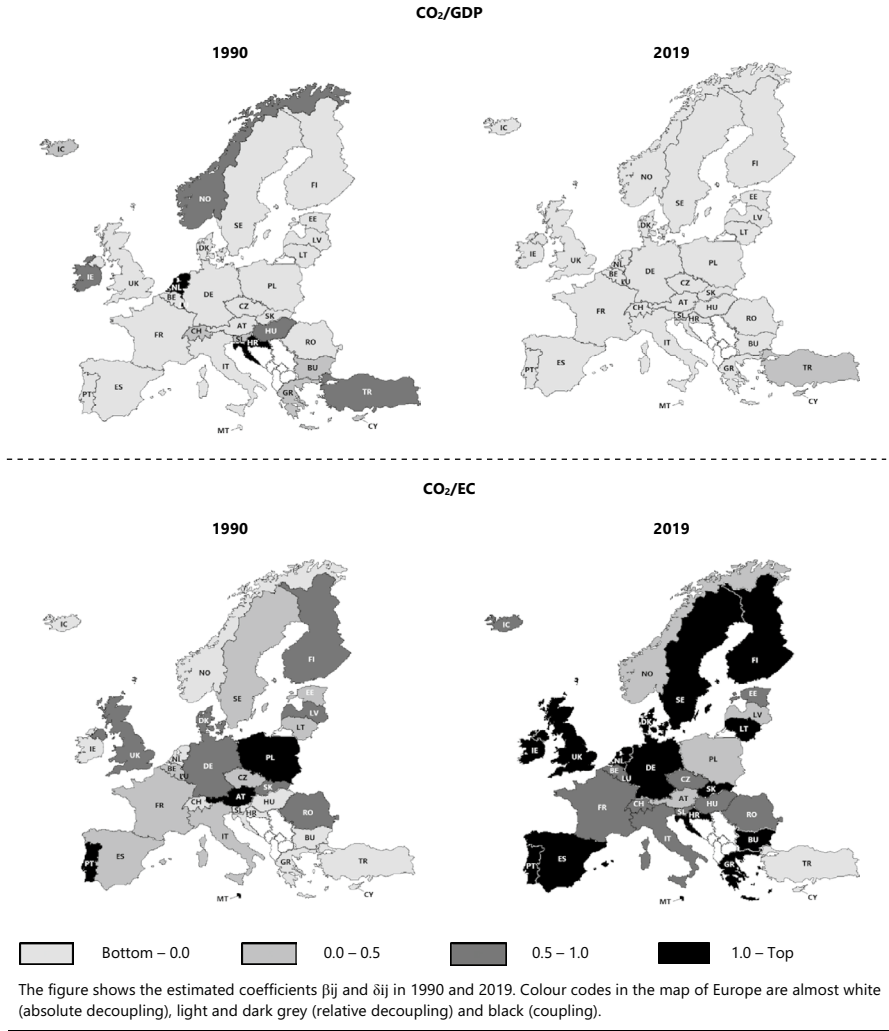


Fig. 2 Elasticities of the energy supply sector CO₂ emissions

now registering the lowest values among all regions. This trend persists even for other countries with values close to or exceeding one in 1990, such as Croatia, Hungary, Ireland, Luxembourg, or Turkey.

In contrast, the situation for energy consumption presents a different scenario. While an increase in GDP generally correlates with a reduction in emissions, this is not the case for emissions related to energy consumption. For all European countries, the situation has worsened dramatically, especially for the South and Western European countries. Hence, substantial efforts are required to prevent further environmental degradation.

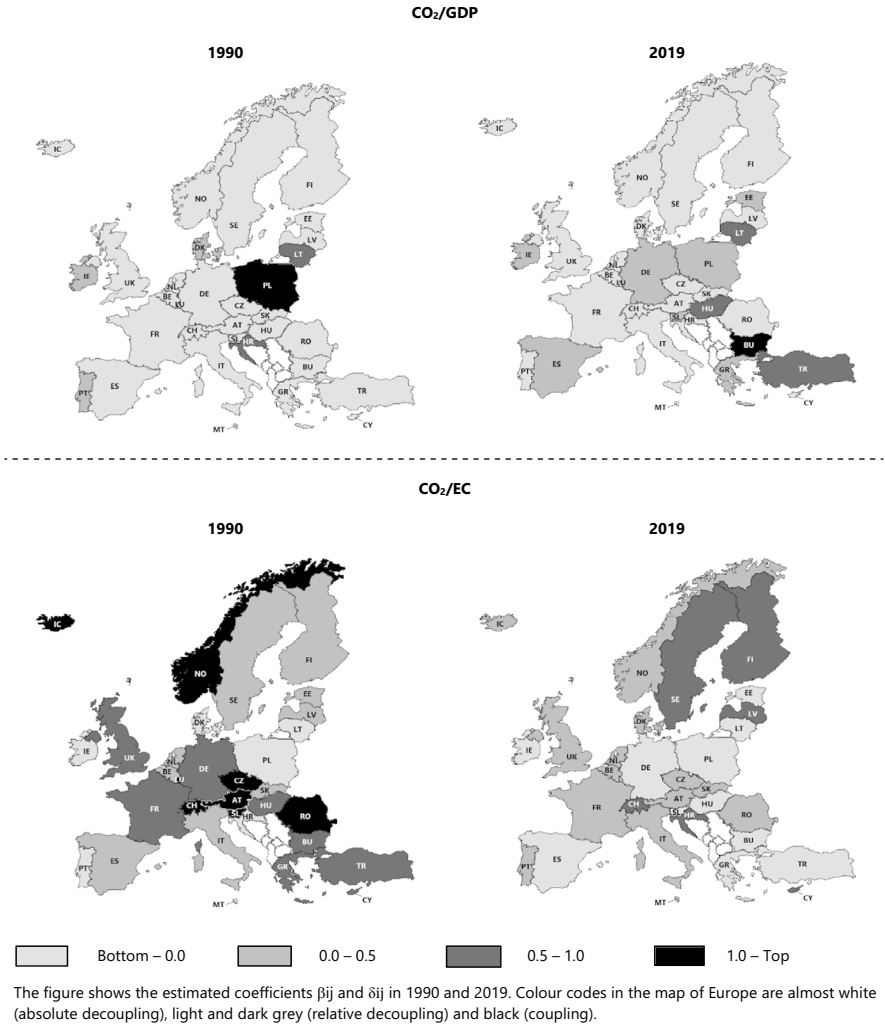


Fig. 3 Elasticities of the industry sector CO₂ emissions

Currently, 16 out of the 32 analyzed countries, including Bulgaria, Croatia, Denmark, Finland, Germany, Greece, Ireland, Lithuania, Luxembourg, Malta, Netherlands, Portugal, Slovakia, Spain, Sweden, and the UK, exhibit absolute coupling of emissions and energy consumption. The pervasive reliance on fossil fuels impedes environmental protection efforts, underscoring the urgent need to transition away from such sources for sustainable decarbonization in European regions.

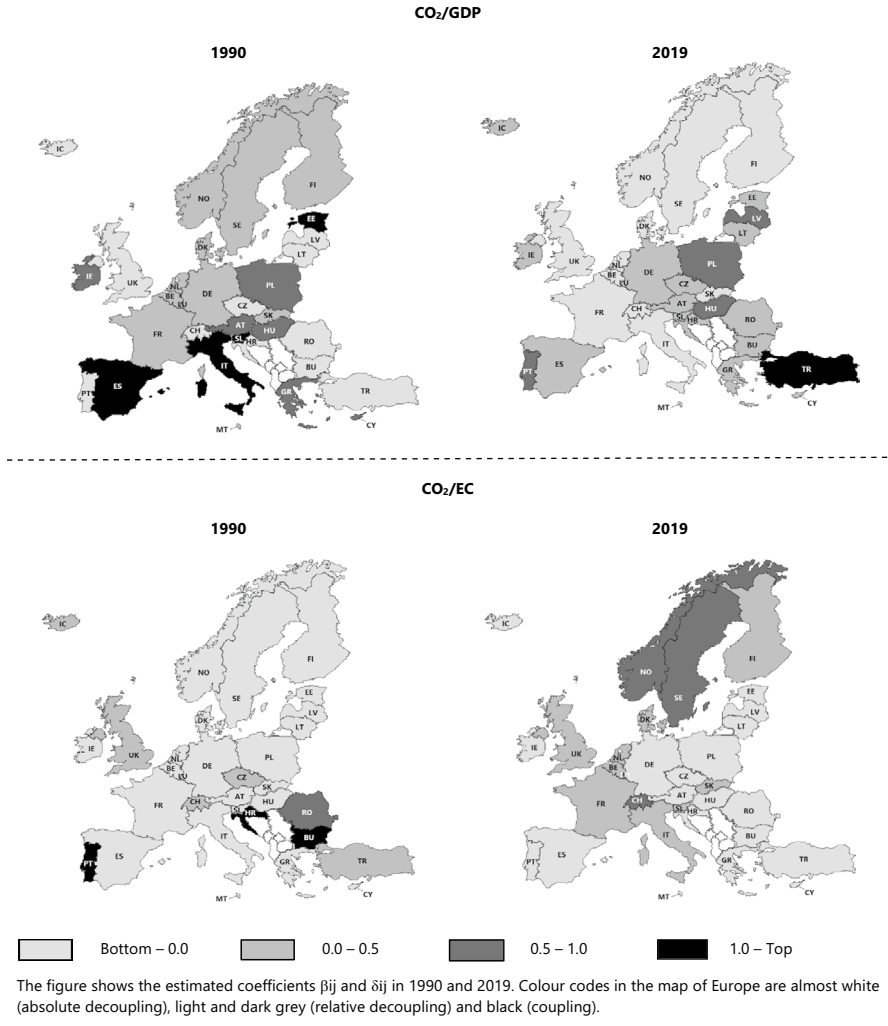


Fig. 4 Elasticities of the domestic transport sector CO₂ emissions

4.2.2 Industry sector

Examining the decoupling process between industry emissions and GDP reveals that while Northern, Southern, and Western European regions demonstrate absolute decoupling, Central and Eastern Europe exhibits relative decoupling, with Central Europe experiencing the least favorable evolution. Countries such as Croatia and Poland, which had high positive elasticities in 1990, have shown significant improvement. Conversely, others like Bulgaria, Hungary, Turkey, and to a lesser

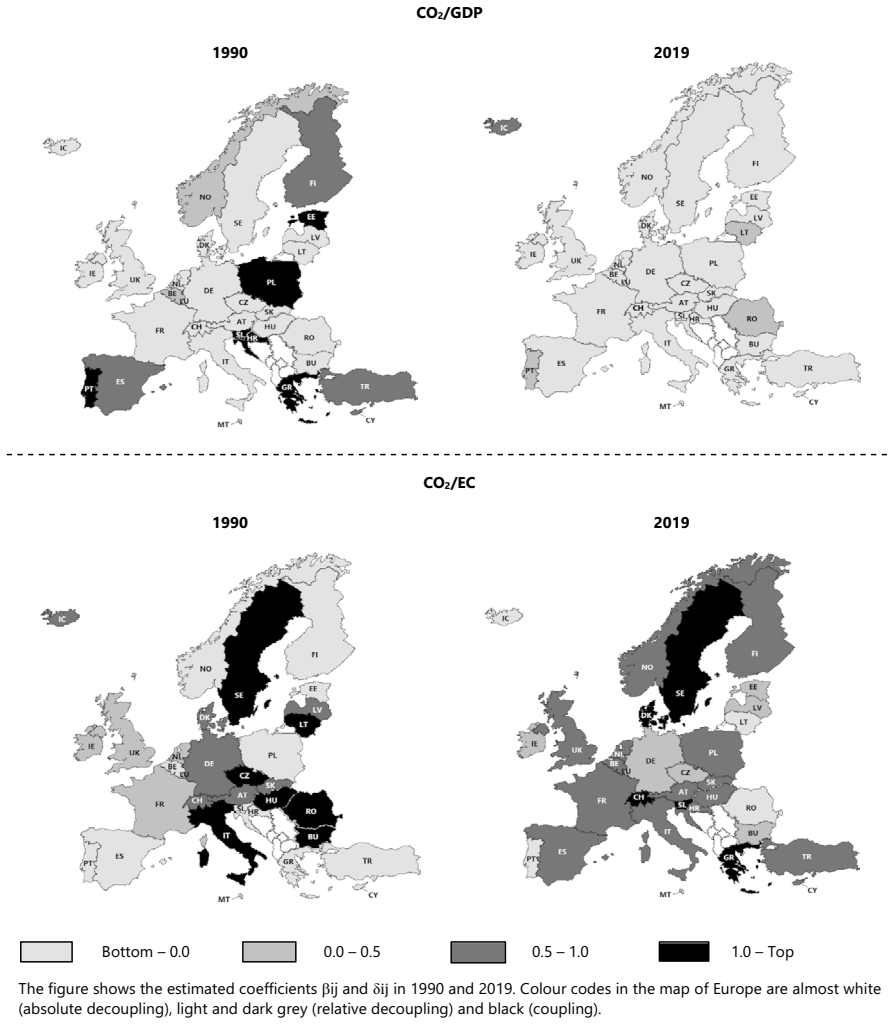


Fig. 5 Elasticities of the residential sector CO₂ emissions

extent, Greece, have made considerable strides toward coupling economic growth and pollution.

The effects of EC on industry emissions present two divergent narratives. Central and Eastern Europe exhibit absolute decoupling, while the rest of the European regions do not. This underscores the reindustrialization process in these areas after the collapse of the former USSR, improving industrial efficiency in terms of energy intensity. Unlike in the other economic sectors, in the Industry Sector, we observe a notable enhancement of energy consumption related to emissions for most of the

countries at the end of 2019, except Croatia, Denmark, Finland, Latvia, Malta, Portugal, and Sweden.

4.2.3 Domestic transport sector

Results for domestic transport CO₂ emissions differ from those of other sectors. The CO₂/GDP elasticity is the most responsive to changes across the entire period compared to other economic sectors. Generally, elasticities of CO₂/GDP have decreased, with notable cases in Estonia, Italy, Slovenia, and Spain. While improvements are noted in all regions, except some Eastern European countries, only the Northern and Western regions exhibit negative values, indicating absolute decoupling. Six countries (Germany, Hungary, Malta, Poland, Switzerland, and the UK) remain stable.

The effects of EC on domestic transport emissions are unclear at the end of the period, with variations in estimated values across countries. The estimated values decreased in some countries, with Croatia, Bulgaria, and Portugal showing the greatest progress toward decoupling. By contrast, in Luxembourg, Norway, Sweden, and Switzerland the value of the elasticity has increased. The domestic transport sector presents a sustainability challenge in Europe due to a preference for private transport and a reliance on road transportation for goods. Despite advancements in transport techniques, this sector remains energy-intensive, predominantly reliant on non-renewable energy, limiting its environmental friendliness.

4.2.4 Residential sector

The overall elasticity of residential sector CO₂ emissions and GDP has reduced, indicating that most countries have decoupled growth from pollution in this sector. Only Iceland, Lithuania, and Romania exhibit a coupled relationship. Linkages between CO₂ emissions and EC have worsened across regions, with all regions showing total coupling in 2019. The energy-intensive nature of residential sectors implies additional emissions associated with higher energy consumption. Current energy consumption patterns remain environmentally harmful in homes across most countries, making decarbonization in the residential sector challenging.

At this point, it is necessary to make a precautionary statement about the results for the Residential Sector CO₂ emissions given the lack of evidence against the unit root inference, as referred to in the previous analysis.

In summary, our findings affirm that the decoupling hypothesis between CO₂ emissions and energy consumption (EC) is less apparent than the observed decoupling between CO₂ emissions and Gross Domestic Product (GDP), which has been a prevalent trend in Europe over the studied period. Undoubtedly, the decoupling process has encountered impediments due to disruptive events in each country over the years. The fulfillment of the decoupling hypothesis between CO₂ and GDP at the end of the period is more pronounced compared to the decoupling between CO₂ and EC. Northern and Western Europe have notably achieved absolute decoupling in the emissions-economy nexus, while disparities in decoupling levels exist across European territories, with Southern countries exhibiting higher levels of decoupling.

compared to their Eastern and Northern counterparts. It is crucial to focus on both consumption patterns and energy sources in endeavors to minimize environmental impact.

In analyzing the interplay between environment, growth, and energy across different economic regions in Europe, it becomes apparent that the findings from various studies vary due to the unique characteristics of each region. This diversity stems from the inclusion of countries with distinct starting points and trajectories. Despite this inherent variability, our research aligns with previous conclusions, albeit with notable regional disparities. We observe a negative long-run elasticity estimate of emissions concerning GDP and a positive elasticity concerning energy consumption in most European countries and economic sectors. These findings are consistent with the results of Acaravci and Ozturk (2010), who studied nineteen European countries from 1960 to 2005, as well as Kasman and Duman (2015), who analyzed a panel of EU countries from 1992 to 2010 and drew similar conclusions. They suggest that the reduction of emissions in the future is unlikely if economic output and energy consumption continue to increase.

Cruz and Dias (2016) emphasize the critical need to transition toward more sustainable economies in Europe. The trend of increasing GDP and energy use from 1999 to 2009 raises concerns about CO₂ intensity. For instance, Cruz and Dias (2016) underscore a common trend of increased real output growth across all geographic groups, encompassing the Center, East, North, and South of Europe. However, when examining energy use patterns, disparities emerge. East European countries such as Bulgaria, Estonia, Lithuania, and Romania experience an uptick in energy consumption, while the Central (e.g., Austria, France, Germany) and Southern (e.g., Italy, Portugal, Spain) regions witness predominantly declining trends. The study by Sanyé-Mengual et al. (2019) highlights distinctions in decoupling levels across European territories. Southern countries like Italy, Portugal, and Greece exhibit higher levels of decoupling compared to their Eastern and Northern counterparts, including Estonia, Finland, Latvia, and Lithuania. These findings underscore the spatial disparities within Europe concerning environmental impacts, economic growth, and energy dynamics.

The spatial disparities within Europe concerning environmental impacts, economic growth, and energy dynamics are evident. For instance, disparities in energy consumption patterns are observed, with East European countries experiencing an uptick in energy consumption, while the Central and Southern regions witness predominantly declining trends (Maraun et al. 2010). Their study also highlights the influence of local contexts on urban diffusion processes and the importance of empirical research carried out on a spatial scale (Salvati and Carlucci 2015; Salvati and Morelli 2014). Regional changes in wind energy potential over Europe have been projected to show significant changes in energy density, particularly in seasonal terms (Hueging et al. 2013). Additionally, the increase in energy transfer over Eurasia and the North Atlantic has been found to enhance low-frequency wave activity and summer droughts, impacting energy dynamics and environmental conditions (Zhang et al. 2020). Furthermore, the interdependence between financial development, fiscal instruments, and environmental degradation in developed and converging EU countries has been identified, highlighting the intricate relationship

between economic factors and environmental impact (Ziolo et al. 2020). Moreover, the impact of institutions on economic and environmental performance has been analyzed, revealing that improving the quality of economic institutions can induce an increase in the scale of economic activity, subsequently affecting CO₂ emissions per capita (Panteli & Delipalla 2022). These factors collectively contribute to the comprehensive understanding of the spatial disparities within Europe concerning environmental impacts, economic growth, and energy dynamics.

In conclusion, the spatial characteristics and underlying causes of disparities in Europe are multifaceted and encompass various aspects such as economic agglomeration, energy consumption patterns, urban diffusion processes, and habitat suitability assessments. Understanding these spatial dynamics is crucial for formulating effective policies and strategies to minimize environmental impact and promote sustainable economic growth across different regions in Europe.

5 Conclusions and policy implications

This study delves into the intricate relationships and evolving dynamics among carbon dioxide emissions, economic growth, and energy consumption across a diverse range of European countries from 1990 to 2019. Despite Europe's perception of insulation from climate change risks due to advanced national welfare states and high political cooperation, this research underscores the vulnerability of the region to environmental degradation, necessitating a proactive approach.

Utilizing the Bai and Perron (1998, 2003a, b) methodology, we implement a dynamic model that relaxes the assumption of parameter stability, allowing for variations in elasticities over time. Our findings affirm the presence of structural breaks, indicative of shifts in the trend of elasticities, corresponding to diverse national or international disturbances such as economic, financial, political, social, or environmental events. This analysis enables us to scale Europe's progress in reducing emissions across major economic sectors relative to economic growth and energy consumption, contributing empirical evidence to the ongoing discourse on energy transition in Europe.

Unit root inference analysis confirms clear connections between emissions, economic growth, and energy consumption in Europe, albeit with heterogeneity across countries. Historical shocks significantly affect this relationship, with breaks concentrated in three distinct periods: the mid-1990s, early 2000s, and the Great Recession (2008–2013) and subsequent European sovereign bonds crisis. The Great Recession intensified polarization among European countries.

The decoupling hypothesis between CO₂ emissions and EC is less evident than that observed between CO₂ emissions and GDP, representing the general trend in Europe during this period. The decoupling process has faced interferences due to disruptive events in each country. While Northern and Western Europe achieve absolute decoupling for the emissions-economy nexus, attention to consumption patterns and energy sources is crucial to minimize environmental impact. These findings align with previous country-level empirical literature, emphasizing the need for sustainable economic practices in Europe. Various studies support the negative

long-run elasticity of emissions with respect to GDP and positive elasticity concerning energy consumption, with differences among European countries in decoupling levels. The urgency to transition away from fossil sources for energy production is vital for decarbonizing European regions, addressing uncertainties in energy intensity for structural changes in economic activities.

Relative decoupling has been achieved in the energy supply, industry, domestic transport, and residential sectors in most countries, but decoupling remains incipient when analyzing the relationship between emissions and energy consumption for these sectors. State planning is deemed essential for a smooth structural conversion toward renewable energy, coupled with a fair transition for disadvantaged communities. European citizens are urged to demand increased government involvement in environmental preservation through decarbonization policies and low-carbon energy transitions.

This study underscores the necessity for a new conceptual toolbox for policymakers, emphasizing material reduction in production across economic sectors, parallel reductions in consumption through resource conservation, and the promotion of renewable energy sources with clean regeneration cycles. Never the less, the disparities across Europe stem from multifaceted spatial characteristics, encompassing economic agglomeration, energy consumption patterns, urban diffusion processes, and habitat suitability assessments. A comprehensive understanding of these spatial dynamics is essential for designing policies and strategies aimed at mitigating environmental impact and fostering sustainable economic growth throughout Europe's regions.

For future research, investigating the impact of recent events like the COVID-19 pandemic and the current war in Ukraine on the stability of the relationship between emissions, economic growth, and energy consumption would be valuable. These events may have altered welfare and energy security in Europe, warranting a comprehensive examination of their implications.

Appendix A

See Tables 9 and 10.

Table 9 Mean and standard deviations of the used variables

	Energy supply CO ₂			Industry CO ₂			Domestic transport CO ₂			Residential CO ₂			GDP			EC		
	Mean	St. dev		Mean	St. dev		Mean	St. dev		Mean	St. dev		Mean	St. dev		Mean	St. dev	
Austria	1.62	0.25		3.09	0.16		2.50	0.36		1.40	0.32		36,194.82	11,953.30		3594.32	269.81	
Belgium	2.57	0.46		4.10	0.81		2.37	0.15		2.51	0.38		33,794.59	10,849.75		4713.12	331.85	
Bulgaria	3.87	0.46		1.82	0.61		0.90	0.31		0.31	0.15		11,941.18	5701.71		2449.13	178.32	
Croatia	1.52	0.27		1.39	0.23		1.16	0.31		0.66	0.09		17,628.59	6551.08		1875.71	212.46	
Cyprus	2.96	0.39		1.71	0.23		1.88	0.16		0.54	0.10		19,356.74	6187.30		3136.62	308.15	
Czechia	6.33	0.60		3.40	1.01		1.42	0.30		1.57	0.47		23,265.93	9489.64		3972.32	225.23	
Denmark	4.83	1.76		1.43	0.30		2.34	0.12		0.93	0.29		35,602.45	12,448.50		3526.36	340.16	
Estonia	10.32	2.32		1.40	0.49		1.50	0.30		0.46	0.10		18,889.79	10,289.42		3994.64	608.00	
Finland	4.65	1.07		3.12	0.50		2.29	0.14		0.99	0.23		32,149.65	10,761.97		6098.15	492.78	
France	1.02	0.20		2.01	0.37		2.15	0.12		1.35	0.20		30,899.76	9275.80		3854.55	181.93	
Germany	4.66	0.52		2.54	0.35		2.05	0.11		1.96	0.38		34,398.30	11,156.26		3839.30	174.82	
Greece	4.64	0.63		1.95	0.31		1.74	0.22		0.72	0.21		22,912.91	5940.17		2372.45	246.48	
Hungary	2.24	0.46		1.32	0.31		1.04	0.23		1.38	0.23		17,879.11	7818.21		2423.44	102.19	
Iceland	0.47	0.10		5.41	1.18		2.60	0.26		0.09	0.05		36,525.54	11,103.85		13,217.64	4055.41	
Ireland	3.33	0.70		1.94	0.35		2.45	0.53		2.21	0.31		40,124.58	20,848.92		3212.91	355.41	
Italy	2.46	0.40		2.03	0.38		1.98	0.19		1.31	0.09		30,538.73	7519.08		2709.02	248.70	
Latvia	1.23	0.40		0.83	0.22		1.28	0.32		0.67	0.33		16,628.80	8275.84		2076.42	305.86	
Lithuania	1.80	0.65		1.55	0.48		1.37	0.39		0.51	0.32		18,740.26	10,110.13		2389.68	559.98	
Luxembourg	1.20	1.03		6.99	5.66		10.96	2.26		3.32	0.44		70,381.45	28,559.02		8654.79	958.93	
Malta	4.11	1.26		0.37	0.21		1.31	0.13		0.50	0.26		23,912.54	10,680.22		2122.73	233.39	
Netherlands	4.03	0.27		2.83	0.65		2.00	0.13		1.84	0.28		37,661.81	12,364.98		4110.94	225.35	
Norway	3.37	0.39		3.15	0.65		2.73	0.23		0.59	0.15		44,964.17	17,638.26		5319.53	525.22	
Poland	5.36	0.51		1.64	0.25		1.00	0.36		1.24	0.15		16,262.96	8671.22		2438.57	126.19	

Table 9 (continued)

	Energy supply CO ₂		Industry CO ₂		Domestic transport CO ₂		Residential CO ₂		GDP		EC	
	Mean	St. dev	Mean	St. dev	Mean	St. dev	Mean	St. dev	Mean	St. dev	Mean	St. dev
	Portugal	1.91	0.30	1.63	0.17	1.64	0.24	0.40	0.08	22,474.35	7188.94	2060.31
Romania	2.77	0.78	1.91	0.66	0.63	0.16	0.45	0.08	12,840.36	8389.93	1764.95	249.54
Slovakia	2.31	0.63	3.48	0.46	1.22	0.16	1.22	0.35	18,971.12	8739.69	3081.25	191.90
Slovenia	3.10	0.38	1.67	0.25	2.25	0.48	1.01	0.31	23,343.57	8758.52	3225.33	290.50
Spain	2.20	0.44	2.06	0.36	1.95	0.25	0.61	0.08	26,520.22	8740.21	2636.33	300.20
Sweden	1.24	0.19	1.91	0.32	2.12	0.22	0.56	0.37	35,556.45	11,300.37	5159.48	357.64
Switzerland	0.48	0.04	1.31	0.12	2.06	0.14	2.09	0.41	45,063.11	14,439.44	3418.99	185.54
Turkey	1.41	0.41	1.34	0.15	0.69	0.18	0.57	0.13	15,306.87	6866.80	1242.14	295.62
UK	3.44	0.92	1.94	0.56	2.05	0.15	1.75	0.28	34,173.99	8217.60	3387.73	408.09
Panel	2.96	0.36	2.07	0.31	1.72	0.08	1.26	0.15	26,724.27	9654.33	118,079.01	5362.36

Table 10 Averages rates of growth of the used variables for the indicated periods

	Energy supply CO ₂			Industry CO ₂			Domestic transport CO ₂			Residential CO ₂			GDP			EC		
	90-19	90-05	05-19	90-19	90-05	05-19	90-19	90-05	05-19	90-19	90-05	05-19	90-19	90-05	05-19	90-19	90-05	05-19
	Austria	-1.3%	0.7%	-3.1%	0.1%	0.6%	-0.1%	1.6%	3.6%	-0.5%	-1.8%	-0.3%	-3.4%	3.9%	4.0%	3.8%	0.6%	1.7%
Belgium	-1.6%	-0.4%	-2.7%	-1.6%	-0.8%	-2.4%	-0.3%	1.3%	-1.0%	-0.6%	0.6%	-1.9%	3.8%	3.9%	3.6%	-0.2%	0.5%	-1.0%
Bulgaria	-0.4%	-0.9%	0.1%	-1.7%	-2.8%	-0.4%	3.1%	3.6%	3.2%	-3.3%	-6.2%	-0.5%	4.4%	2.5%	6.8%	-0.4%	-1.1%	0.8%
Croatia	-1.0%	1.4%	-3.3%	-1.2%	-0.8%	-1.5%	2.6%	3.4%	1.8%	-0.2%	1.8%	-2.1%	5.8%	6.7%	5.1%	0.4%	1.1%	-0.2%
Cyprus	0.8%	2.7%	-0.9%	0.1%	1.4%	-1.1%	0.4%	1.6%	-0.8%	0.4%	0.4%	-2.3%	4.0%	4.7%	3.5%	0.3%	1.5%	-0.9%
Czechia	-1.0%	0.3%	-2.0%	-3.0%	-3.7%	-2.6%	1.8%	3.1%	0.9%	-3.0%	-4.7%	-2.0%	4.3%	3.8%	5.0%	-0.7%	-0.6%	-0.8%
Denmark	-2.8%	0.3%	-6.6%	-1.4%	0.1%	-3.5%	0.3%	1.2%	-0.6%	-3.3%	-1.7%	-4.7%	4.2%	4.3%	4.2%	-0.5%	0.5%	-1.5%
Estonia	-2.4%	-3.8%	-1.0%	-2.3%	-4.3%	0.1%	1.3%	1.7%	1.2%	-1.5%	-2.4%	-0.9%	7.7%	9.3%	7.0%	-1.3%	-2.7%	0.2%
Finland	0.5%	2.1%	-3.3%	-1.7%	-0.5%	-2.9%	-0.5%	0.1%	-1.2%	-2.5%	-1.8%	-3.2%	3.7%	3.9%	3.5%	0.3%	1.2%	-1.1%
France	-2.2%	-0.6%	-3.2%	-1.8%	-1.1%	-2.4%	-0.2%	0.5%	-1.0%	-1.4%	0.0%	-2.8%	3.6%	3.7%	3.6%	-0.2%	0.7%	-1.1%
Germany	-2.1%	-1.3%	-2.9%	-1.5%	-2.8%	-0.3%	-0.1%	-0.4%	-0.2%	-1.6%	-2.1%	-1.1%	3.7%	3.4%	4.0%	-0.7%	-0.5%	-0.9%
Greece	-1.0%	1.6%	-3.5%	-0.8%	1.1%	-1.9%	0.7%	2.3%	-0.9%	1.0%	5.4%	-2.9%	3.0%	4.5%	1.4%	0.0%	1.8%	-1.7%
Hungary	-1.5%	-0.3%	-3.2%	-1.7%	-3.4%	0.5%	2.1%	2.4%	2.3%	-1.5%	-0.4%	-2.4%	5.2%	5.3%	5.1%	-0.1%	0.0%	0.2%
Iceland	2.5%	3.7%	0.8%	0.9%	-0.4%	1.8%	0.7%	0.9%	0.3%	2.2%	8.4%	-6.1%	3.5%	3.6%	3.4%	2.5%	1.4%	3.4%
Ireland	-1.6%	1.2%	-4.2%	-0.7%	0.7%	-1.9%	2.0%	5.4%	-1.3%	-1.5%	-0.7%	-2.1%	6.8%	7.5%	5.9%	0.4%	1.9%	-1.3%
Italy	-1.5%	0.7%	-3.6%	-1.6%	0.2%	-3.4%	0.0%	1.4%	-1.6%	0.2%	1.5%	-0.7%	3.1%	3.3%	2.9%	0.1%	1.7%	-1.5%
Latvia	-2.7%	-5.7%	0.7%	-1.9%	-5.6%	2.0%	1.7%	1.6%	2.1%	-3.2%	-5.9%	-0.3%	7.8%	9.7%	6.8%	-0.6%	-2.3%	1.4%
Lithuania	-3.7%	-3.6%	-3.2%	0.3%	-1.9%	3.2%	2.1%	-0.2%	4.7%	-3.0%	-7.6%	2.3%	8.3%	9.4%	7.7%	-1.5%	-2.7%	-0.6%
Luxembourg	11.9%	33.2%	-10.5%	-5.8%	-8.6%	-2.9%	1.5%	5.8%	-2.5%	-0.7%	0.3%	-2.0%	5.0%	5.8%	4.4%	-0.7%	0.9%	-2.2%
Malta	-2.7%	0.6%	-6.3%	5.4%	1.4%	7.3%	1.9%	2.7%	1.3%	-2.4%	-5.1%	-2.8%	5.7%	6.0%	5.2%	-0.2%	1.0%	-1.6%
Netherlands	-0.3%	1.0%	-1.7%	-1.9%	-2.2%	-1.5%	-0.1%	1.0%	-1.2%	-0.9%	-0.3%	-1.8%	4.0%	4.6%	3.5%	-0.2%	0.6%	-1.1%
Norway	1.0%	2.6%	-0.8%	-2.1%	-1.9%	-2.5%	-0.1%	1.3%	-1.5%	-1.7%	-1.8%	-2.5%	4.8%	6.7%	3.4%	0.4%	1.9%	-0.9%
Poland	-1.4%	-1.7%	-1.0%	-0.2%	-0.2%	-0.6%	4.3%	4.0%	4.8%	-0.2%	0.1%	-0.2%	6.1%	5.6%	6.5%	0.0%	-0.8%	0.9%
Portugal	0.5%	3.7%	-2.0%	0.1%	1.2%	-1.2%	1.7%	3.9%	-0.7%	0.4%	4.2%	-3.5%	4.0%	4.5%	3.7%	1.3%	3.1%	-0.4%

Table 10 (continued)

	Energy supply CO ₂			Industry CO ₂			Domestic transport CO ₂			Residential CO ₂			GDP			EC		
	90-19	90-05	05-19	90-19	90-05	05-19	90-19	90-05	05-19	90-19	90-05	05-19	90-19	90-05	05-19	90-19	90-05	05-19
Romania	-3.3%	-3.0%	-3.3%	-3.2%	-4.8%	-1.6%	2.7%	1.6%	3.1%	1.3%	2.4%	0.3%	6.7%	4.3%	9.1%	-1.4%	-2.7%	-0.2%
Slovakia	-3.5%	-3.1%	-4.1%	-1.8%	-2.1%	-1.5%	0.8%	1.1%	1.3%	-3.0%	-3.9%	-1.2%	5.8%	6.7%	5.3%	-0.7%	-0.9%	-0.4%
Slovenia	-1.0%	0.3%	-2.3%	-1.4%	-0.8%	-1.4%	2.7%	3.6%	2.1%	-1.0%	3.1%	-5.5%	4.3%	4.6%	4.1%	0.4%	1.7%	-0.6%
Spain	-1.0%	2.7%	-4.2%	-0.6%	2.2%	-3.2%	1.0%	3.0%	-1.1%	0.9%	3.1%	-1.3%	4.0%	4.8%	3.3%	0.7%	2.7%	-1.2%
Sweden	-0.4%	1.3%	-2.7%	-1.1%	-0.1%	-2.2%	-1.1%	0.4%	-2.5%	-6.8%	-6.4%	-8.2%	3.5%	3.5%	3.3%	-0.5%	0.2%	-1.4%
Switzerland	0.0%	1.9%	-1.6%	-1.3%	-0.7%	-1.8%	-0.8%	-0.1%	-1.4%	-1.9%	-0.4%	-3.1%	3.3%	2.6%	4.0%	-0.3%	-0.2%	-0.5%
Turkey	3.3%	4.3%	3.3%	1.0%	2.1%	0.0%	2.7%	1.7%	3.4%	1.9%	0.2%	4.0%	4.4%	2.7%	6.4%	2.5%	2.1%	3.0%
UK	-4.0%	-1.5%	-6.2%	-2.9%	-2.5%	-3.2%	-0.6%	0.2%	-1.3%	-1.0%	-0.3%	-2.0%	3.7%	4.8%	2.8%	-1.0%	0.4%	-2.2%
Panel	-1.9%	-0.7%	-2.9%	-1.7%	-1.5%	-1.8%	0.4%	1.1%	-0.3%	-1.2%	-0.7%	-1.5%	4.0%	4.1%	3.9%	-0.1%	0.3%	-0.5%

Appendix B

See Tables 11, 12, 13, 14, 15, 16.

Table 11 Testing for unit roots. Per capita energy supply sector CO₂ emissions

	DF-GLS	KPSS	LS1	TB1	LS2	TB1	TB2
Austria	-0.95	0.20**	-3.25***	2004	-3.72*	1993	2006
Belgium	-1.46	0.22***	-4.16*	2010	-6.57	2001	2011
Bulgaria	-1.24	0.14*	-3.94*	2007	-5.52**	2001	2009
Croatia	-1.43	0.27***	-4.57***	2001	-5.45**	1998	2002
Cyprus	-1.65	0.24***	-3.03*	2010	-5.47**	1993	2004
Czechia	-1.40	0.25***	-3.67*	2005	-5.59**	2004	2015
Denmark	-0.89	0.17**	-5.42	1998	-7.90	1997	2010
Estonia	-1.41	0.18**	-3.06*	2001	-4.78*	1994	2008
Finland	-1.48	0.25***	-4.69***	2001	-5.76***	1997	2003
France	-2.30	0.17**	-3.93*	2004	-4.80*	1997	2004
Germany	-1.31	0.13*	-2.22*	2001	-3.61*	2000	2015
Greece	-0.72	0.29***	-1.56*	2000	-6.07***	2002	2015
Hungary	-1.41	0.24***	-3.44*	2000	-4.34*	1996	2009
Iceland	-1.98	0.19**	-3.04*	2011	-4.23*	1993	2009
Ireland	-1.29	0.26***	-2.12*	2004	-4.51*	2001	2013
Italy	-1.11	0.28***	-1.79*	2010	-3.87*	2000	2007
Latvia	-1.63	0.26***	-2.67*	2002	-3.87*	1996	2002
Lithuania	-3.52***	0.14*	-5.01***	1994	-6.06***	1994	2014
Luxembourg	-1.06	0.25***	-2.19*	2009	-7.75	2003	2012
Malta	-1.48	0.23***	-3.62*	2002	-7.05	1998	2002
Netherlands	-0.98	0.22***	-4.56***	1998	-4.90*	1996	1999
Norway	-1.01	0.30***	-3.52*	2002	-6.40***	1993	2004
Poland	-1.85	0.19**	-3.92*	2001	-5.14*	1993	2001
Portugal	-1.52	0.17**	-4.06*	1997	-5.13*	2006	2015
Romania	-3.79***	0.06	-4.74***	2004	-5.93***	1996	2002
Slovakia	-1.99	0.08	-2.12*	1999	-3.81*	1994	2004
Slovenia	-1.13	0.24***	-3.93*	2014	-5.27*	2001	2013
Spain	-1.32	0.25***	-4.02*	2001	-5.60***	1999	2002
Sweden	-1.11	0.12*	-4.63***	2013	-6.05***	1998	2001
Switzerland	-0.95	0.27***	-3.91*	2005	-8.37	2004	2014
Turkey	-2.60	0.08	-3.64*	2005	-4.46*	2005	2013
UK	-0.99	0.22***	-3.12*	2004	-5.30*	1997	2007

DF-GLS and KPSS are the statistics proposed by Elliott et al. (1996) and Kwiatkowski et al. (1992) enhanced by the work of Hobjin et al. (2004), respectively, when the specification includes an intercept and a deterministic trend. LS_i is the Lagrange Multiplier (LM)-type statistic proposed by Lee and Strazicich (2003) when the specification includes *i* breaks that affect both the intercept and the deterministic trend with *i* = 1, 2

***Rejection of the unit root null hypothesis for a 1% significance level

**Rejection of the unit root null hypothesis for a 5% significance level

*Rejection of the unit root null hypothesis for a 10% significance level

Table 12 Testing for unit roots. Per capita industry sector CO₂ emissions

	DF-GLS	KPSS	LS1	TB1	LS2	TB1	TB2
Austria	-2.01	0.19**	-4.82***	2005	-7.21	2006	2009
Belgium	-1.92	0.17**	-3.60*	2006	-5.38**	1994	2008
Bulgaria	-3.31**	0.10	-4.19*	2015	-6.73	2004	2009
Croatia	-1.81	0.14*	-1.89*	1999	-3.87*	1994	2007
Cyprus	-2.43	0.07	-4.02*	2009	-5.37**	2009	2013
Czechia	-0.47	0.17**	-3.69*	2000	-5.47**	1994	2009
Denmark	-1.34	0.23***	-2.79*	1998	-3.94*	2002	2008
Estonia	-1.49	0.13*	-4.53***	1996	-5.91***	1995	2004
Finland	-1.48	0.25***	-3.98*	2007	-4.60*	2006	2013
France	-2.73	0.13*	-5.67	2008	-6.65	1997	2008
Germany	-1.31	0.27***	-3.78*	2004	-7.37	1994	1999
Greece	-1.65	0.19**	-2.68*	1993	-5.52**	2003	2009
Hungary	-1.70	0.20**	-3.61*	1995	-4.86*	1995	2015
Iceland	-1.94	0.11	-3.04*	2006	-3.88*	1997	2005
Ireland	-1.99	0.18**	-3.23*	1993	-4.48*	2000	2012
Italy	-1.56	0.25***	-3.13*	2007	-5.63**	1999	2002
Latvia	-1.52	0.22***	-2.72*	1997	-4.12*	1993	2012
Lithuania	-1.46	0.10	-4.98***	1998	-6.56	1995	2004
Luxembourg	-1.19	0.25***	-6.39	1999	-7.53	1996	1999
Malta	-1.76	0.23***	-3.00*	2004	-5.87***	2012	2015
Netherlands	-1.59	0.20**	-4.84***	2011	-4.95*	1999	2007
Norway	-2.74	0.11	-2.92*	1997	-5.94***	1995	2008
Poland	-2.75	0.08	-4.13*	2000	-6.86	1993	1999
Portugal	-1.50	0.23***	-3.00*	2007	-5.52**	1998	2014
Romania	-0.64	0.20**	-4.23**	1996	-4.57*	1996	2007
Slovakia	-2.38	0.09	-3.48*	2016	-3.86*	1995	2002
Slovenia	-2.65	0.09	-2.66*	2007	-4.51*	1996	2008
Spain	-1.21	0.27***	-2.85*	2007	-5.88***	2004	2013
Sweden	-1.71	0.23***	-6.13	1995	-6.82	1993	2007
Switzerland	-1.60	0.19**	-4.63***	2007	-4.66*	1995	2005
Turkey	-0.81	0.07	-4.80***	2000	-4.96*	2000	2009
UK	-2.46	0.11	-2.91*	2010	-4.03*	2006	2009

DF-GLS and KPSS are the statistics proposed by Elliott et al. (1996) and Kwiatkowski et al. (1992) enhanced by the work of HobjinHobijn et al. (2004), respectively, when the specification includes an intercept and a deterministic trend. LS_i is the Lagrange Multiplier (LM)-type statistic proposed by Lee and Strazicich (2003) when the specification includes *i* breaks that affect both the intercept and the deterministic trend with *i*=1,2

***Rejection of the unit root null hypothesis for a 1% significance level

**Rejection of the unit root null hypothesis for a 5% significance level

* Rejection of the unit root null hypothesis for a 10% significance level

Table 13 Testing for unit roots. Per capita domestic transport sector CO₂ emissions

	DF-GLS	KPSS	LS1	TB1	LS2	TB1	TB2
Austria	-1.15	0.23***	-3.92*	2001	-4.78*	2001	2013
Belgium	-1.39	0.28***	-3.29*	2004	-4.17*	2008	2014
Bulgaria	-1.79	0.09	-3.47*	1998	-4.37*	1993	2008
Croatia	-2.00	0.18**	-8.43	2011	-4.97*	2012	2015
Cyprus	-2.01	0.25***	-3.10*	2006	-4.36*	2010	2015
Czechia	-1.61	0.15**	-3.96*	2012	-5.72**	2004	2015
Denmark	-1.60	0.23***	-4.08*	2009	-4.78*	1993	2009
Estonia	-2.26	0.08	-4.17*	2002	-11.19	1994	2004
Finland	-1.55	0.23***	-2.97*	2005	-4.03*	1994	2007
France	-1.55	0.25***	-2.31*	2004	-4.26*	2002	2007
Germany	-1.54	0.14**	-1.91*	2003	-5.10*	1999	2005
Greece	-1.59	0.24***	-3.79*	2010	-4.63*	2007	2010
Hungary	-2.30	0.10	-2.18*	2008	-3.71*	2005	2010
Iceland	-2.38	0.09	-2.93*	2005	-3.96*	2002	2009
Ireland	-1.58	0.27***	-2.83*	2003	-3.59*	1997	2009
Italy	-1.47	0.28***	-2.57*	2006	-3.95*	2003	2010
Latvia	-2.27	0.10	-2.66*	2009	-4.43*	1998	2009
Lithuania	-3.20***	0.18**	-7.21	1993	-8.08	1995	2001
Luxembourg	-1.33	0.26***	-3.78*	2002	-5.21*	2001	2008
Malta	-1.72	0.13*	-4.67***	1998	-5.90***	1999	2002
Netherlands	-1.18	0.28***	-3.29*	2007	-4.77*	2007	2013
Norway	-0.63	0.26***	-2.11*	2010	-4.52*	1995	2013
Poland	-3.51**	0.11	-4.76***	1998	-5.55**	1999	2009
Portugal	-1.73	0.27***	-2.74*	2004	-4.08*	1999	2009
Romania	-1.01	0.15**	-3.62*	1997	-4.68*	1994	2013
Slovakia	-1.98	0.08	-2.99*	1995	-4.35*	1993	2010
Slovenia	-2.94*	0.07	-3.28*	2009	-4.49*	1998	2008
Spain	-1.53	0.25***	-2.27*	2004	-3.66*	2001	2009
Sweden	-0.62	0.29***	-2.71*	2006	-4.49*	1996	2006
Switzerland	-1.28	0.23***	-3.57*	2008	-3.55*	1996	2011
Turkey	-2.07	0.22***	-4.16*	1999	-4.53*	2006	2013
UK	-1.82	0.24***	-2.70*	2002	-3.50*	2001	2010

DF-GLS and KPSS are the statistics proposed by Elliott et al. (1996) and Kwiatkowski et al. (1992) enhanced by the work of Hobijn et al. (2004), respectively, when the specification includes an intercept and a deterministic trend. LSi is the Lagrange Multiplier (LM)-type statistic proposed by Lee and Strazicich (2003) when the specification includes i breaks that affect both the intercept and the deterministic trend with $i=1,2$

***Rejection of the unit root null hypothesis for a 1% significance level

**Rejection of the unit root null hypothesis for a 5% significance level

* Rejection of the unit root null hypothesis for a 10% significance level

Table 14 Testing for unit roots. Per capita residential sector CO₂ emissions

	DF-GLS	KPSS	LS1	TB1	LS2	TB1	TB2
Austria	-1.52	0.22***	-5.36	2006	-7.18	2005	2010
Belgium	-1.94	0.22***	-5.33	2004	-6.82	1994	2011
Bulgaria	-1.24	0.27***	-5.48	2002	-7.29	1993	2001
Croatia	-1.84	0.23***	-3.53*	2005	-5.11*	2004	2012
Cyprus	-1.82	0.24***	-4.12*	2002	-4.81*	1999	2003
Czechia	-2.06	0.25***	-4.75***	1997	-5.30*	2000	2008
Denmark	-2.42	0.08	-5.62	1998	-6.43	1997	2010
Estonia	-1.93	0.10	-5.78	1994	-8.23	1994	2009
Finland	-1.87	0.13*	-3.28*	2001	-5.44**	1996	2006
France	-1.47	0.23***	-4.99***	2002	-5.95***	1993	2005
Germany	-1.16	0.08	-6.06	2002	-7.42	1994	1997
Greece	-1.34	0.28***	-2.97*	2007	-3.99*	1994	2007
Hungary	-2.99*	0.07	-3.52*	2002	-4.98*	1999	2006
Iceland	-1.87	0.17**	-5.85	2005	-7.84	1996	2006
Ireland	-1.57	0.19**	-3.21*	2010	-4.70*	1997	2010
Italy	-1.79	0.21***	-4.24**	2010	-4.93*	1994	2010
Latvia	-1.67	0.20**	-5.64	1996	-6.20***	1997	2003
Lithuania	-3.02*	0.22***	-6.33	1995	-16.18	1994	2001
Luxembourg	-1.91	0.19**	-5.30	2005	-6.20***	1999	2014
Malta	-1.68	0.15**	-2.55*	2013	-4.95*	1997	2007
Netherlands	-3.11*	0.08	-5.51	1997	-6.81	1997	2008
Norway	-1.23	0.06	-3.78*	2005	-4.98*	1994	1998
Poland	-1.91	0.14**	-2.83*	2000	-5.64**	2007	2010
Portugal	-1.32	0.27***	-5.12	2000	-4.39*	2000	2015
Romania	-1.71	0.09	-4.23**	2005	-4.96*	1998	2006
Slovakia	-0.87	0.18**	-4.32**	1993	-5.28*	1993	2005
Slovenia	-1.24	0.25***	-3.47*	2002	-6.04***	1996	2008
Spain	-1.17	0.27***	-3.13*	2011	-4.00*	2003	2012
Sweden	-0.52	0.25***	-3.33*	1993	-5.35**	1998	2006
Switzerland	-1.32	0.25***	-6.82	2002	-7.19	1994	2002
Turkey	-1.85	0.16**	-3.26*	2007	-4.66*	2002	2009
UK	-1.23	0.24***	-5.83	1995	-7.20	2005	2013

DF-GLS and KPSS are the statistics proposed by Elliott et al. (1996) and Kwiatkowski et al. (1992) enhanced by the work of Hobijn et al. (2004), respectively, when the specification includes an intercept and a deterministic trend. LS_i is the Lagrange Multiplier (LM)-type statistic proposed by Lee and Strazicich (2003) when the specification includes i breaks that affect both the intercept and the deterministic trend with $i=1,2$

***Rejection of the unit root null hypothesis for a 1% significance level

**Rejection of the unit root null hypothesis for a 5% significance level

*Rejection of the unit root null hypothesis for a 10% significance level

Table 15 Testing for unit roots. Per capita GDP

	DF-GLS	KPSS	LS1	TB1	LS2	TB1	TB2
Austria	- 1.31	0.27***	- 5.01***	2005	- 5.83***	1995	2010
Belgium	- 1.02	0.24***	- 6.01	2007	- 5.35**	2005	2011
Bulgaria	- 0.75	0.27***	- 2.28*	1997	- 3.23*	1997	2000
Croatia	- 3.01*	0.06	- 4.00*	2009	- 6.79***	2004	2011
Cyprus	- 3.69**	0.08	- 4.75***	2009	- 6.42	2003	2010
Czechia	- 1.01	0.23***	- 2.90*	1995	- 4.51*	2002	2010
Denmark	- 0.85	0.24***	- 2.33*	2011	- 4.90*	2005	2014
Estonia	- 1.52	0.17**	- 4.00*	1997	- 5.11*	2003	2011
Finland	- 2.68	0.07	- 2.98*	2009	- 4.76*	1995	2011
France	- 1.59	0.17**	- 2.96*	2012	- 5.30*	2000	2009
Germany	- 1.20	0.29***	- 2.55*	2009	- 6.49	1998	2002
Greece	- 2.17	0.20**	- 3.77*	2005	- 6.50	2005	2013
Hungary	- 0.64	0.22***	- 2.03*	2007	- 5.85***	1994	2013
Iceland	- 2.55	0.12*	- 3.23*	2016	- 5.29*	2005	2010
Ireland	- 1.37	0.15**	- 2.89*	2008	- 4.37*	1994	2002
Italy	- 3.18*	0.05	- 4.73***	2011	- 5.40**	1998	2011
Latvia	- 1.96	0.13*	- 3.41*	1997	- 5.10*	2004	2011
Lithuania	- 1.55	0.21**	- 2.99*	2000	- 4.71*	1999	2008
Luxembourg	- 2.60	0.16**	- 3.10*	1995	- 4.35*	2004	2009
Malta	- 0.55	0.26***	- 3.53*	2012	- 5.44**	1996	2003
Netherlands	- 3.30**	0.06	- 3.71*	2009	- 4.42*	1997	2009
Norway	- 1.20	0.15**	- 4.88***	2007	- 6.39***	2001	2007
Poland	- 0.20	0.30***	- 3.03*	2003	- 4.12*	1993	2005
Portugal	- 2.37	0.07	- 3.78*	2009	- 5.58**	2006	2012
Romania	- 0.65	0.27***	- 2.54*	1998	- 4.02*	2003	2011
Slovakia	- 1.61	0.15**	- 6.16	2005	- 5.05*	1999	2007
Slovenia	- 1.88	0.09	- 2.77*	2009	- 3.39*	2003	2011
Spain	- 3.46**	0.08	- 3.98*	2009	- 5.52**	2003	2011
Sweden	- 1.45	0.16**	- 5.53	1993	- 4.69*	1994	1999
Switzerland	- 1.41	0.25***	- 3.50*	2009	- 5.66***	2001	2009
Turkey	- 1.36	0.28***	- 1.91*	2006	- 4.10*	1994	1999
UK	- 1.72	0.10	- 2.98*	2008	- 5.56**	1997	2010

DF-GLS and KPSS are the statistics proposed by Elliott et al. (1996) and Kwiatkowski et al. (1992) enhanced by the work of Hobjin et al. (2004), respectively, when the specification includes an intercept and a deterministic trend. LS_i is the Lagrange Multiplier (LM)-type statistic proposed by Lee and Strazicich (2003) when the specification includes i breaks that affect both the intercept and the deterministic trend with $i=1,2$

***Rejection of the unit root null hypothesis for a 1% significance level

**Rejection of the unit root null hypothesis for a 5% significance level

*Rejection of the unit root null hypothesis for a 10% significance level

Table 16 Testing for unit roots. Per capita EC

	DF-GLS	KPSS	LS1	TB1	LS2	TB1	TB2
Austria	-0.78	0.27***	-4.57***	2004	-5.43**	2003	2014
Belgium	-1.44	0.26***	-3.60*	2000	-5.86***	1995	2011
Bulgaria	-1.58	0.13*	-3.30*	2002	-3.91*	2002	2014
Croatia	-1.88	0.21**	-3.97*	2009	-5.49**	2012	2015
Cyprus	-1.57	0.23***	-3.39*	2009	-6.37	1996	2000
Czechia	-1.96	0.11	-2.97*	2002	-3.89*	1996	2003
Denmark	-1.45	0.22***	-3.75*	2011	-5.76***	1997	2010
Estonia	-2.53	0.19**	-2.94*	2001	-4.60*	1993	2008
Finland	-1.30	0.28***	-4.51*	2006	-5.60**	2002	2012
France	-1.03	0.29***	-4.72***	2003	-5.27*	1999	2007
Germany	-1.90	0.16**	-4.84***	2001	-6.42	1995	2004
Greece	-1.05	0.29***	-2.60*	2000	-3.13*	1998	2009
Hungary	-2.45	0.07	-2.61*	2005	-3.58*	2003	2012
Iceland	-1.96	0.12*	-3.25*	2006	-5.61**	1993	2014
Ireland	-1.32	0.26***	-1.72*	2010	-2.87*	1996	2010
Italy	-0.96	0.29***	-2.92*	2006	-4.42*	2004	2013
Latvia	-2.37	0.20**	-3.49*	2002	-5.31*	1997	2006
Lithuania	-1.91	0.12*	-4.51***	2002	-5.71**	1997	2003
Luxembourg	-1.78	0.17**	-2.65*	2008	-3.67*	2001	2009
Malta	-2.09	0.20**	-5.60	2012	-6.47	2002	2014
Netherlands	-1.13	0.28***	-3.58*	2008	-5.73***	1994	2011
Norway	-1.37	0.25***	-5.33	2009	-6.23***	2000	2008
Poland	-1.92	0.21***	-3.28*	1999	-5.31**	2000	2006
Portugal	-1.25	0.27***	-2.17*	1999	-4.89*	2000	2011
Romania	-2.45	0.14**	-3.48*	2002	-4.06*	1999	2008
Slovakia	-1.77	0.08	-3.52*	2001	-4.39*	2001	2014
Slovenia	-1.33	0.27***	-3.73*	2008	-5.83***	2007	2013
Spain	-1.27	0.26***	-2.21*	1999	-5.20*	2001	2015
Sweden	-1.57	0.23***	-5.09***	2005	-5.43**	1993	2005
Switzerland	-1.50	0.18**	-4.37**	2009	-5.27*	1996	2009
Turkey	-1.48	0.20**	-4.30**	2015	-5.99***	2006	2015
UK	-2.15	0.29***	-2.26*	2006	-4.17*	2003	2009

DF-GLS and KPSS are the statistics proposed by Elliott et al. (1996) and Kwiatkowski et al. (1992) enhanced by the work of Hobjin et al. (2004), respectively, when the specification includes an intercept and a deterministic trend. LS_i is the Lagrange Multiplier (LM)-type statistic proposed by Lee and Strazicich (2003) when the specification includes *i* breaks that affect both the intercept and the deterministic trend with *i* = 1, 2

***Rejection of the unit root null hypothesis for a 1% significance level

**Rejection of the unit root null hypothesis for a 5% significance level

*Rejection of the unit root null hypothesis for a 10% significance level

Author contribution Jesús Lucindo was involved in conceptualization, methodology, formal analysis, investigation, writing—original draft, writing—review & editing. Marisa Feijóo helped in conceptualization, methodology, formal analysis, investigation, writing—original draft, writing—review & editing. María A. González—Álvarez assisted in conceptualization, methodology, formal analysis, investigation, writing—original draft, writing—review & editing.

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Data and Code availability The dataset generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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